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SURFACE WAVES: SOURCE AND PATH PROPERTIES

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The seismic surface wave contains information about the depth of the source. To extract this information, the effect of propagation must be known. We find that unconsolidated sediments can effectively erode the short period energy. The results of this study suggest that much care must be taken before the absence of short period surface waves is interpreted as an effect of focal depth.

Deep earthquakes definitely exhibit a different Rayleigh wave amplitude

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than shallow events. In addition, a higher mode Rayleigh wave appears to dominate the long period vertical record. We conclude that both phenomena may be used as a depth diagnostic. We failed to confirm the utility of source phase for identifying deep events. The source phase may be useful for resolving shallow depth events.

INTRODUCTION

We have been investigating the properties of seismic surface waves with the ultimate goal of using these waves to determine the mechanism and depth of the source. This information will be useful to discriminate explosions from earthquakes. Our approach has been to choose events whose depths vary significantly so as to identify gross effects of depth on the surface wave. The major source regions with widely differing focal depths are subduction zones. We thus focused on a small number of events in the Lesser Antilles Arc area for part of the study.

One major aspect of deducing the source effect on the surface wave is the removal of propagation effects. Since subduction zones are inherently bordered by ocean, it was necessary to study the effect of oceanic propagation on the surface wave. To this end we investigated surface waves from mid-Atlantic ridge earthquakes.

DATA BASE

Properties of the earthquakes used in this study are given in table 1. The focal mechanisms for the mid-Atlantic ridge earthquakes were previously well characterized by their Rayleigh wave signals and body wave first motions (Weidner and Aki, 1973). The focal mechanisms for the Lesser-Antilles events were determined from first motions of compressional waves which were recorded at stations of the WWSSN. Most of the observations were from the long period instruments and the data are illustrated in figure 1. The surface waves used in this study are from the long period instruments of the WWSSN. Rayleigh waves were generally obtained from the vertical component while Love waves were obtained by a coordinate rotation of the N-S and E-W recordings. In all cases the seismograms were digitized to allow computer analyses of the wave train.

PATH EFFECTS

Short Period Surface Waves

Depth resolution for depths shallower than 10 km is dependent on surface wave analyses for periods shorter than about 20 sec. It is therefore important to understand how the propagation path can affect short period surface waves. We have studied Rayleigh waves from mid-Atlantic ridge earthquakes (Weidner, 1972) and Love waves from the same earthquakes (Weidner, 1975) with the conclusion that oceanic sediments dominate the short period surface wave character (Weidner, 1975). From theoretical models we find that a surficial layer with a low shear velocity severely affects surface waves with a period of

$$T = \frac{4H}{\beta}$$

where H is the thickness of the low velocity layer and β is the shear velocity. The group velocity for this period is extremely low, the eigen functions (stress and displacement with depth) are considerably perturbed, and an additional mode exists at shorter periods. These phenomena can give rise to an erosion of the surface wave energy for periods shorter than the longest period which is severely affected by the low-velocity layer along the path. The energy loss could be either from scattering due to impedence barriers or attenuation if the low-velocity layer has a low Q since energy is trapped in this layer.

Observations of both Love and Rayleigh waves support the theoretical predictions. Generally, shallow normal faulting earthquakes should excite short period Rayleigh waves at a higher level than

the long periods. Weidner and Aki (1973) concluded that the normal faulting events on the mid-Atlantic ridge were shallow. The conclusions were based on phase analyses of the period range 20-50 sec. The Rayleigh wave amplitude for periods shorter than 20 sec were however, quite low. Based on these amplitudes Tsai (1969) previously concluded that these events were much deeper (greater than 40 km). The absence of the short period Rayleigh waves is consistent with the shallow depth if the sediments along the propagation path are responsible for the loss of these short periods as suggested by the theoretical models. During the course of this study (reported in the first scientific report) we have pursued the effect of sediments by searching for corroborative observations. We found additional evidence from an analysis of the Love waves observed from these earthquakes. Love waves should propagate without much dispersion even at short periods, over an oceanic structure with no sediments. We found, however, that the Love wave dispersion at short periods was quite pronounced with the same character as the Rayleigh wave. We carefully determined that the Love wave signal was not contaminated with the horizontal Rayleigh wave. This type of dispersion would result if both the short period Love and Rayleigh wave dispersion was controlled by the sediments.

A further confirming observation is from an analysis of the Love wave amplitudes. The expected source spectral amplitude for Love waves is difficult to define since the excitation of short periods is strongly controlled by the upper mantle structure beneath the source. However, Love waves differ from Rayleigh waves in that

the excited spectral shape is independent of the azimuth of the observing station. Thus, all stations should exhibit identical spectral shapes. This was not observed. In general, stations which recorded low amplitude Rayleigh waves at short periods also exhibit comparable Love wave spectral shapes. We conclude that the path must be controlling Love wave spectral shapes and therefore also the Rayleigh wave spectral shapes.

Finally, for paths with very deep sediments both Love and Rayleigh waves exhibit evidence of a higher mode at periods shorter than that of the minimum group velocity. These paths in fact appear to indicate a period as long as 40 sec which is being critically perturbed by the sediments. Such a long period is consistent with the observed sediment thickness of 5 km and inferred shear velocity of .5 km/sec.

The conclusions of these observations are applicable on a broader scope than just oceanic propagation. The presence of the water layer has essentially no effect on the theoretical models. Thus, thick unconsolidated continental sediments can be expected to give comparable results. A major point of this study regarding depth discriminants is the definition of limitations on the utility of surface waves. By judiciously choosing propagation paths we may not be misled into deducing path effects as source effects.

<u>Long Period Surface Waves</u>

The periods longer than 20 sec for most paths do not suffer marked attenuation. The major path effect for these periods is a phase delay. Weidner and Aki (1973) illustrate the potential of using source phase for a depth diagnostic. Thus, it is important

to know the phase velocities quite accurately for the paths traversed. These phase velocities can be accurately calculated if the upper mantle velocity structure is well known. We have analyzed the phase velocity of Love waves. We found that the upper mantle structure deduced for the normal ocean basin from Rayleigh waves (Weidner, 1974) was consistent with the Love wave phase velocities. We did find some paths (along the ocean ridge) where the observations did not agree with the previously defined model. The disagreement has not yet been resolved. Furthermore, we have not investigated the degree to which Rayleigh wave phase velocities could be predicted from the Love wave phase velocities. In principle if this could be done, the Rayleigh wave phase velocity could be calculated independently of the observed Rayleigh wave phase. Then corrections for propagation to the observed phase could be made so as to deduce the source phase. While the logic of such an approach is somewhat circular, it may be possible to simultaneously constrain the source and the path using the observed phase for both Love and Rayleigh waves.

SOURCE EFFECTS

The relative excitation of surface wave modes as well as the source amplitude and phase spectra for each mode of Love and Rayleigh waves depends on the depth and mechanism of the source. These properties will also depend on the medium structure in the vicinity of the source. Viable depth diagnostics will reflect properties of the observed wave train that depend most on the focal depth and least on the indeterminant factors such as medium structure. Our analyses of Love waves particularly for an oceanic structure suggest that Love wave spectral amplitudes do not satisfy these criteria. The spectral shape is extremely sensitive to properties of the source medium. Additionally, since the group velocities of the fundamental and higher modes are very similar, it is difficult to determine the relative amplitudes or to accurately determine the phase. We have thus focused our attention on Rayleigh waves. We have examined the Rayleigh wave recorded at a few stations for both deep and shallow events where the events were close. The paths from the events to a station will be similar and the differences observed at the station should reflect the differences in the source. We now present a tentative evaluation of the utility of higher modes, source amplitude spectra, and source phase spectra for depth determinations.

Higher Modes

Unlike Love waves, oceanic Rayleigh wave higher modes propagate with a different group velocity from the fundamental mode. This

allows us to identify the higher mode distinct from the fundamental mode. The arrival of energy as a function of group velocity and period can be calculated with the technique of Dziewonski et al. (1969). The results of the analysis for the vertical long period component recorded at three stations corresponding to up to three events is shown in figure 2. The curves are energy contours with no correction for instrument. The results for the 8 July 70 event indicate large amplitudes for a wave that is not the fundamental mode. This wave appears dispersed and is probably a higher mode Rayleigh wave. The records for NAT and SHA are more conclusive than BEC. BEC, however, is closer to the event giving less time for the two waves to separate. This event is located at a depth of 150 km. The analysis for the event of 15 May 1969 (50 km depth) indicates the arrival of the same wave (with a group velocity of about 4.6 km/sec at 25 sec). The amplitudes of these arrivals are however much lower than the fundamental mode.

The recording of the shallowest event (7 January 1970) was not digitized to include the fast arrival in the time window. Since the records were digitized prior to the analysis, the time window was determined by the recorded energy on the seismogram and since no surface wave was apparent on the record at such early times, this segment of the record was not included. Our qualitative conclusion is that the higher mode for this record is even of lower relative amplitude than on the 15 May 1969 record.

We tentatively conclude from these observations that the ratio of fundamental mode amplitude to higher mode amplitude of Rayleigh waves is very sensitive to focal depth, at least for widely differing

depths. Furthermore, at least for oceanic paths, the group velocities differ sufficiently to resolve the two modes.

These suggestions now need to be quantified. The wave identification must be verified and the depth resolution must be defined. The above conclusions depend on a correct identification of the higher mode. Various body wave phases could possibly produce the observed signals. An unambiguous identification can be made by comparing the relative phase of the vertical and radial signals. This requires that the horizontal components be digitized and rotated to radial and transverse. The vertical and radial components could be time variable filtered with a filter designed to enhance the higher mode signal and eliminate the fundamental mode. The phases of the two components could then be directly compared. If they are in phase or 180° out of phase, the signal is a body wave. If they are out of phase by +90° or -90° then the signal is a higher mode Rayleigh wave. The amplitude ratio of higher to fundamental mode can be calculated from the amplitudes of a time variable filter, designed for the higher mode and from one designed for the fundamental mode.

The next step is to investigate the expected excitation using theoretical models, this analysis can be readily accomplished. The medium structure must first be assumed. Then the eigenfunctions (stress and displacement with depth) can be calculated for the fundamental mode and higher modes as a function of frequency. The excitation of each surface wave can be calculated as a function of azimuth by introducing the double couple source at the appropriate depth. Once the expected excitations are known, the observed values

can be compared to test the theoretical predictions. Additionally, theoretical amplitude ratios of higher to fundamental modes can be calculated for many focal mechanisms and depths. The results of this analysis will be very useful to define the depth resolution obtainable with this approach. Furthermore, ambiguities introduced by uncertain focal mechanisms can be studied.

The final stage of analysis should involve looking at many stations for many events. With greater amounts of data path effects can be studied and the overall utility of such an approach can be carefully evaluated.

Fundamental Mode Amplitudes

The dependence of Rayleigh wave amplitude on frequency is sensitive to the source depth. Such data were used by Tsai (1969) to deduce focal depths of mid-ocean ridge earthquakes. We have since shown that more care must be exercised in including path effects for these events, but such information may still be usable as a depth diagnostic.

We have investigated the amplitude spectrum of the fundamental mode Rayleigh wave for records previously discussed. The first step in the analysis is to remove, as much as possible, the higher mode from the record. We attempted this by passing the record through a time variable filter designed to enhance the fundamental mode. The technique is described by Landisman et al. (1969). A given period, T, is windowed in time by the function

$$\begin{aligned} W(t) &= 0 & t &< ta \\ W(t) &= \cos\left\{\frac{\pi(t-(X/U(T)))}{t_b - ta}\right\}; & ta &< t < t_b \\ W(t) &= 0 & t &> t_b \end{aligned}$$

where x is the epicentral distance, U(T) is the group velocity for the period T as obtained in the last section, and

$$t_a = \frac{X}{U(T)} - T\left(\alpha + \beta \left|\frac{dU(T)}{dT}\right|\right)$$

$$t_b = \frac{X}{U(T)} + T\left(\alpha + \beta \left|\frac{dU(T)}{dT}\right|\right)$$

We used $\alpha = 3.5$ and $\beta = 60$. The resultant amplitudes are illustrated in figure 3. These amplitudes have not been corrected for instrument response. In all cases the ratio of hi frequency amplitude to low frequency amplitude decreases with depth. This qualitative behavior is consistent with the theoretical results shown in figure 4.

Before a quantitative comparison is useful we must make a few further steps. First, we must carefully examine the effect of the time variable filter on these records. The time window must be narrow enough to eliminate the higher mode. Furthermore, we must be careful that the higher mode does not influence the results because of the order that the various steps are performed. Secondly data from more stations should be analyzed to give a more comprehensive data base. This data will be useful in more precisely defining the focal mechanism. Nevertheless, the data that have been analyzed definitely indicate that the shape of the amplitude spectrum is sensitive to focal depth. Now the resolution must be carefully analyzed.

<u>Fundamental Mode Phase</u>

Weidner and Aki (1973) illustrated the utility of phase as a depth diagnostic. In that case all events were shallow. We have obtained the phase of the time variable filtered records of these events. Using the approach of Weidner and Aki (1973), the difference in focal phase for two events at one station was calculated. This

quantity is insensitive to path since the epicenters were quite close. Thus, the path phase delay cancels when we subtract the individual phases. The results of this analysis are given in figure 5. Here the observed values are compared with theoretical values. In general we find that the comparison is not good, indicating that phase is not a good depth diagnostic for these events. There could be many reasons for this. First, with the limited data set, the earthquake mechanism may be in error. Phase is more sensitive to the details of the mechanism than is amplitude. More Rayleigh wave data would help define the mechanism.

Another problem may stem from the time variable filtering process. Generally the phase difference of the time variable filtered records appear to smooth the phase difference of the unfiltered record. Yet the higher mode dominated the short period amplitudes of the deeper event. Thus, the unfiltered phase should not correlate with the filtered phase. This suggests that the filter is not eliminating the effect of the higher mode.

A final problem is that the fundamental mode has a very low amplitude for the deep event. This was made clear by comparing the two seismograms recorded at NAT. At the time of fundamental mode ground motion for the 15 May 1969 event there was no similar wave train on the 8 July 1970 record. Thus, noise may be dominating the fundamental mode of the deep event.

CONCLUSION

We have investigated the path and source effects on surface waves. We conclude that unconsolidated sediments severely affect the short period surface wave. Such sediments may remove information that would otherwise be important for resolving shallow focal depths. In fact, if the path effect is not taken into account, grossly erroneous depths may be concluded.

The analysis of Love waves suggest that the utility of Love waves as a depth diagnostic may be quite limited. We must emphasize that we are examining source regions and paths that are dominated by ocean. We cannot definitely rule out a Love wave diagnostics for continental regions.

We have examined Rayleigh waves from events with a considerable depth difference. We find that the ratio of fundamental mode amplitude to higher mode amplitude is depth dependent. We also find that the shape of the amplitude spectrum is depth dependent. We did not, however, confirm the utility of phase analyses as a depth diagnostic.

The depth resolution of these analyses must now be made. We have discussed the studies that must be made to discern this. We may well find that higher mode generation and amplitude spectral shape can be used to roughly define the focal depth and that for shallow events, the phase may have the greatest resolving power.

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TABLE 1

EARTHQUAKE DATA

Date	Origin Time UT	Location	Depth RM	Strike	Dip Deg	Slip	Magnitude
2 June 1965	23:40:22	15.96°N,46.79°W	3.5	15	50	-100	5.6
10 June 1970	14:25:18	15.4°N,45.9°W	6	8	86	160	5.6
8 July 1970	4:49:10.6	17.96°N,64.63°W	150	75	120	60	5.8
15 May 1969	20:43:33	16.75°N,61.34°W	50	-26	104	-88	5.7
7 January 1970	7:56:11	15.88°N,59.73°W	25	49	62	20	5.7

FIGURE CAPTIONS

Figure 1

Compressional wave first motions for Lesser-Antilles events. Solid circles are compression, open circles are dilitation, an "X" indicates an uncertain reading

Figure 2

Equal energy contours of the vertical Rayleigh wave component as a function of period and group velocity. A plus indicates a local maximum and a minus indicates a minimum.

Figure 3

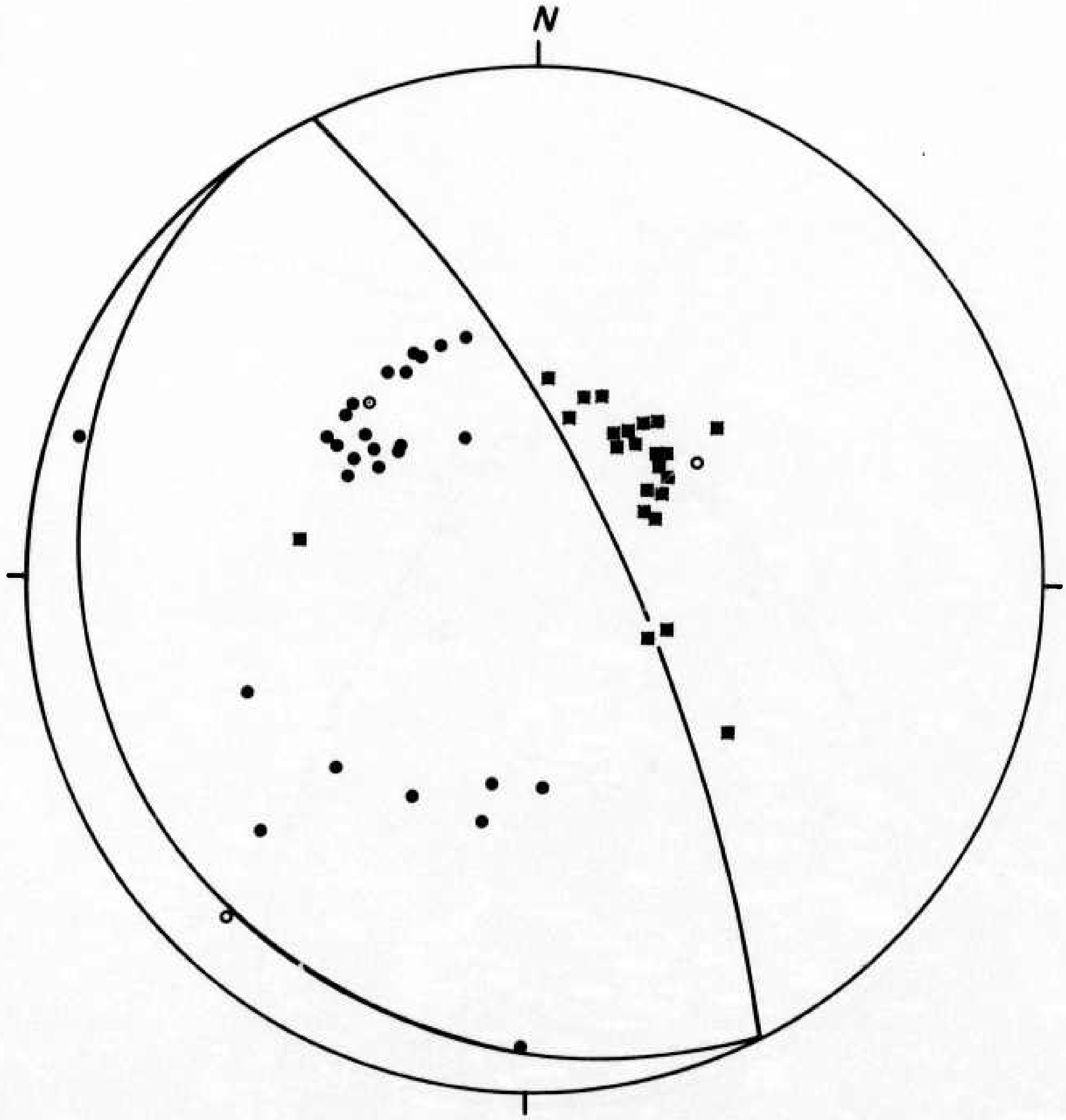
Observed Rayleigh wave spectral amplitude from the time variable filtered record.

Figure 4

Theoretical Rayleigh wave amplitude for different focal depths.

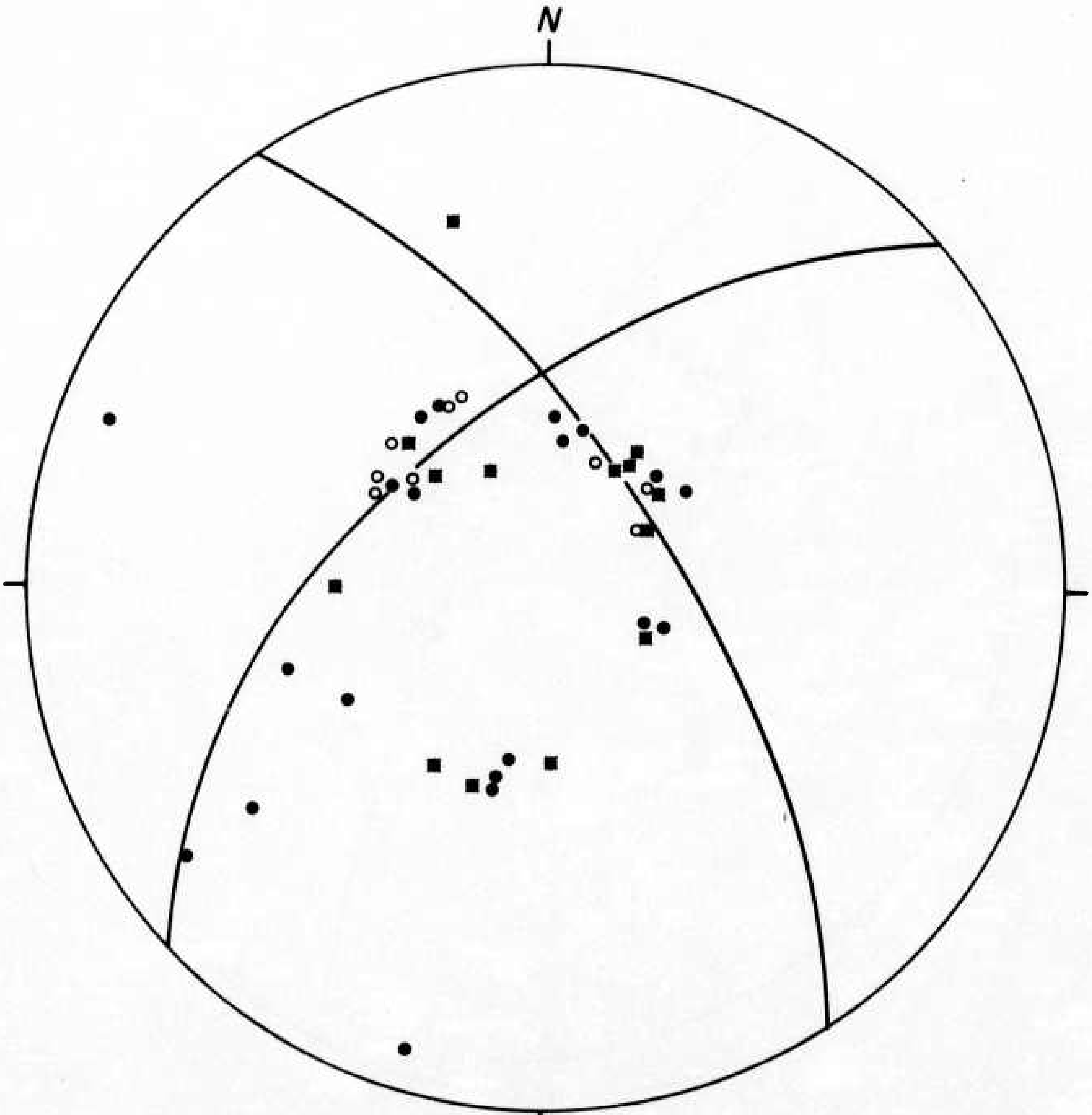
Figure 5

Observed and theoretical differential phase. The observed values are from the time variable filtered records.



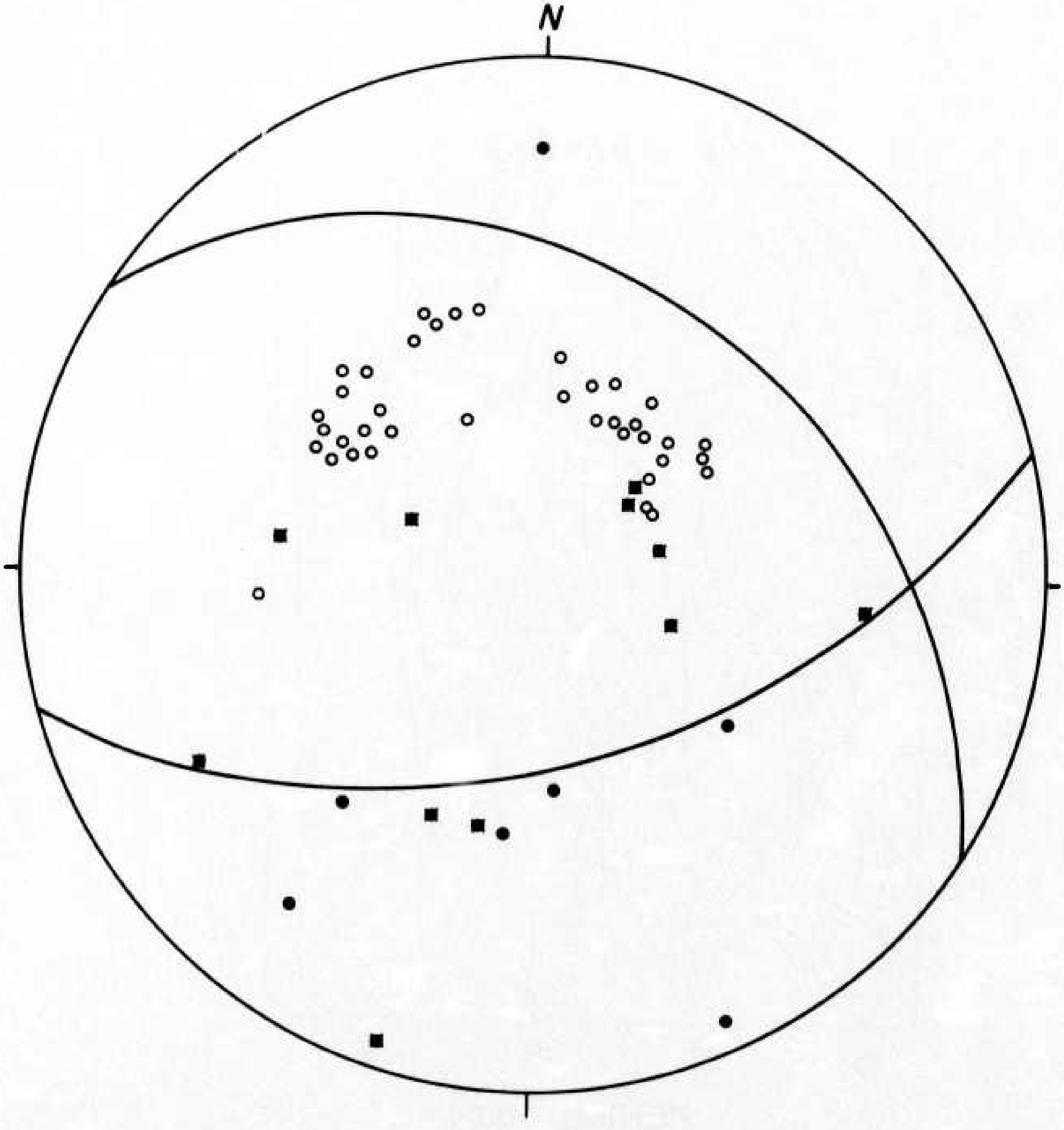
5 MAY 1969

Figure 1a.



7 JAN 1970

Figure lb.



8 JULY 1970

Figure 1c.

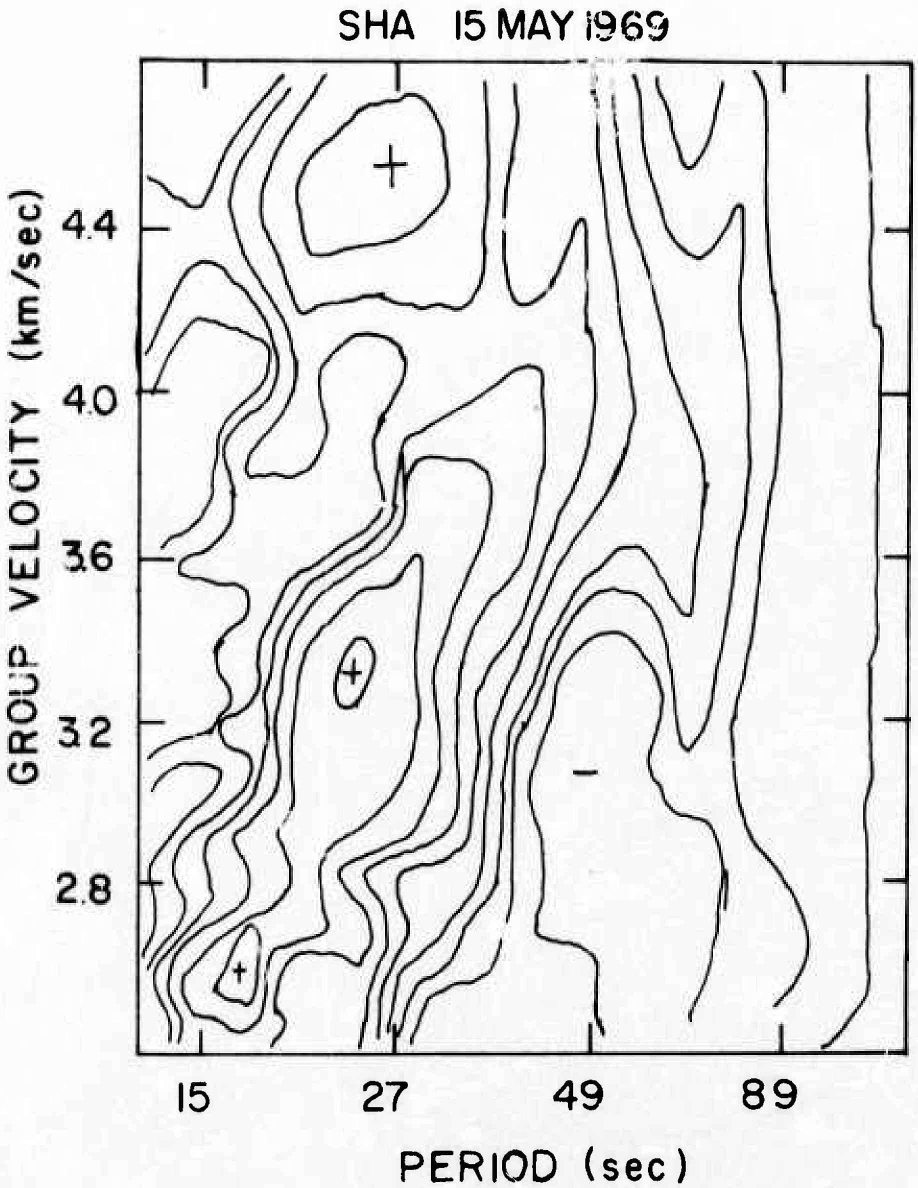

SHA 15 MAY 1969
GROUP VELOCITY (km/sec)
4.4
4.0
3.6
3.2
2.8
15
27
49
89
PERIOD (sec)

Figure 2a.

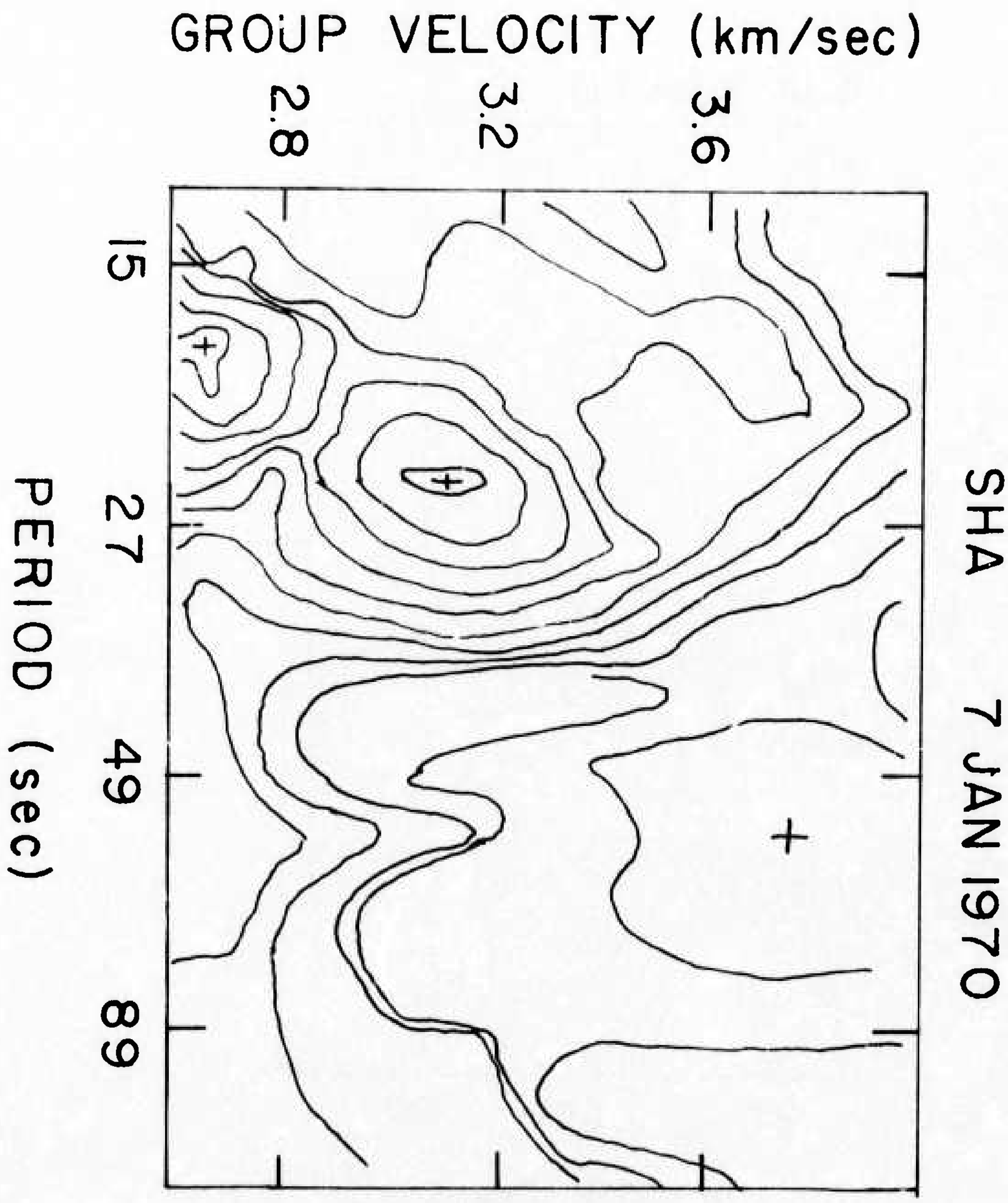

GROUP VELOCITY (km/sec)
2.8
3.2
3.6
15
27
49
89
PERIOD (sec)
SHA 7 JAN 1970

Figure 2b.

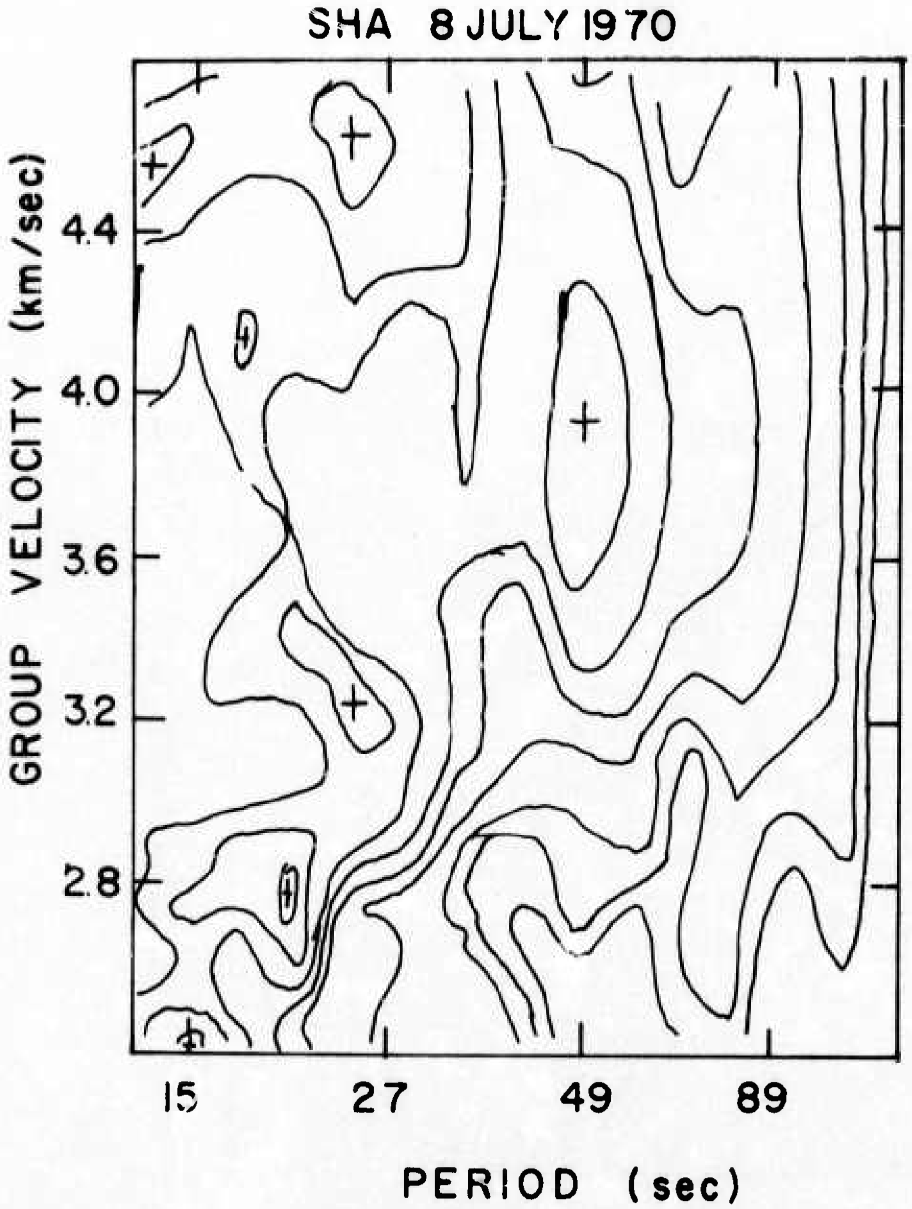

SHA 8 JULY 1970
GROUP VELOCITY (km/sec)
4.4
4.0
3.6
3.2
2.8
15
27
49
89
PERIOD (sec)

Figure 2c.

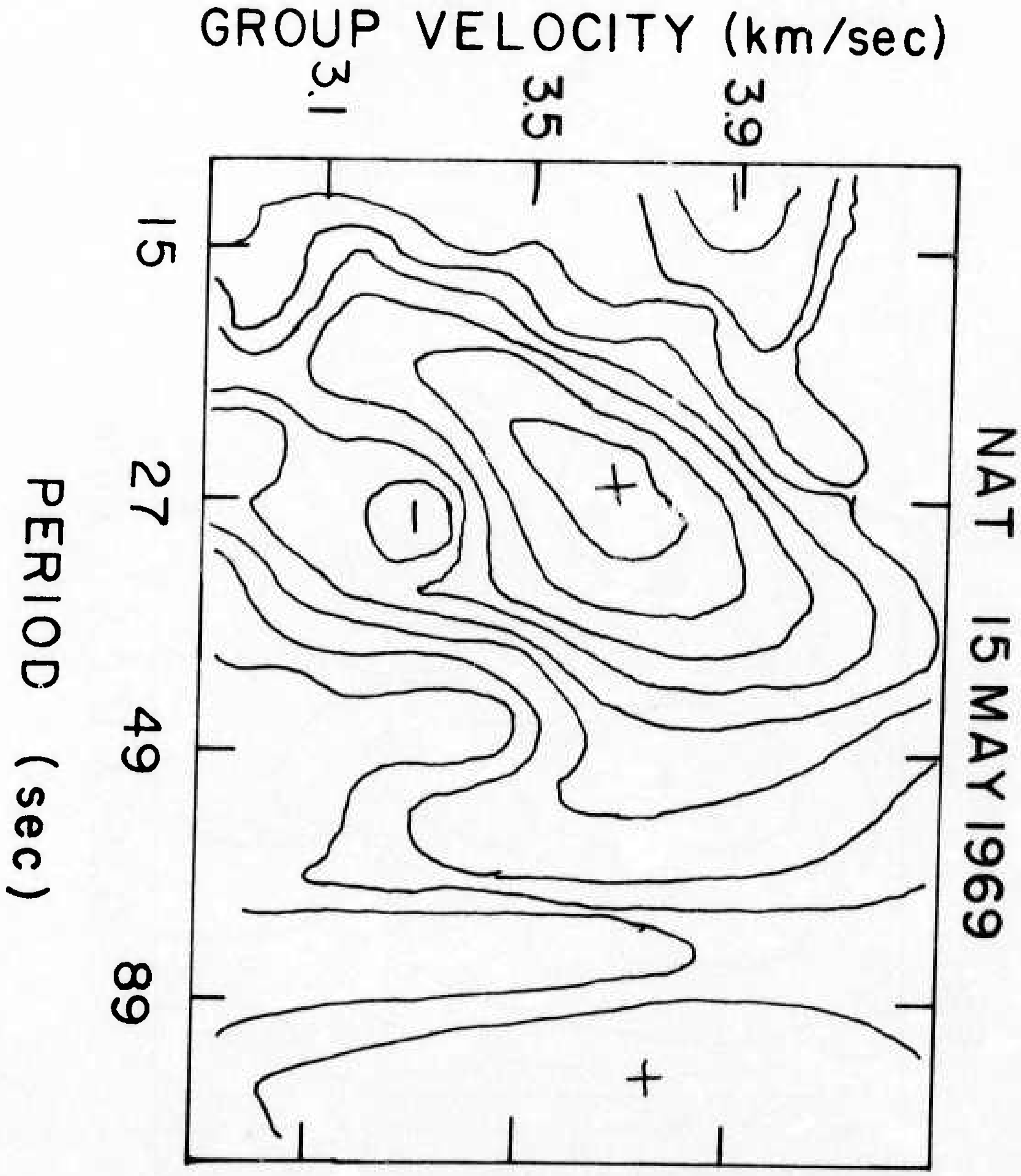

GROUP VELOCITY (km/sec)
3.1
3.5
3.9
15
27
49
89
PERIOD (sec)
NAT 15 MAY 1969

Figure 2d.

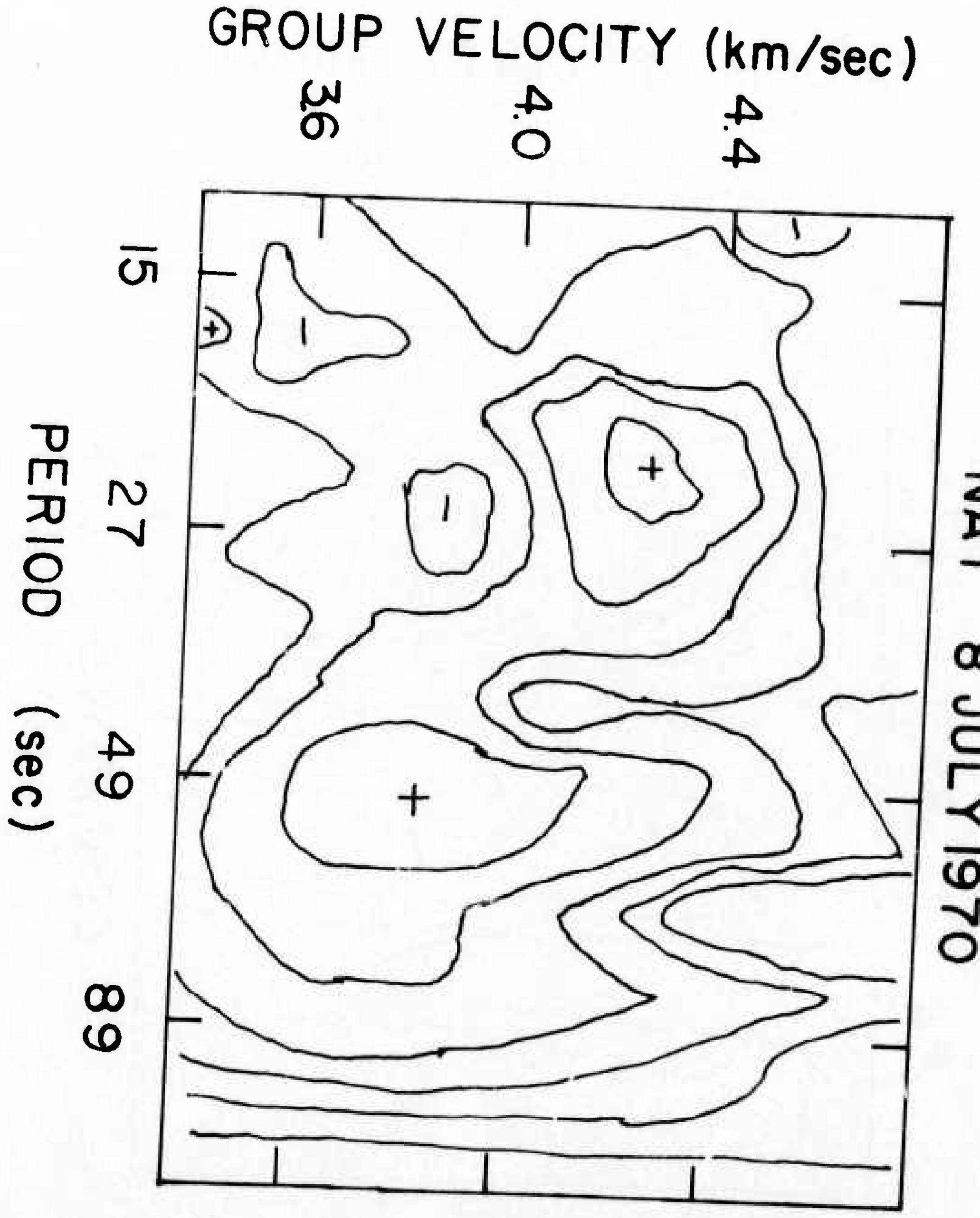
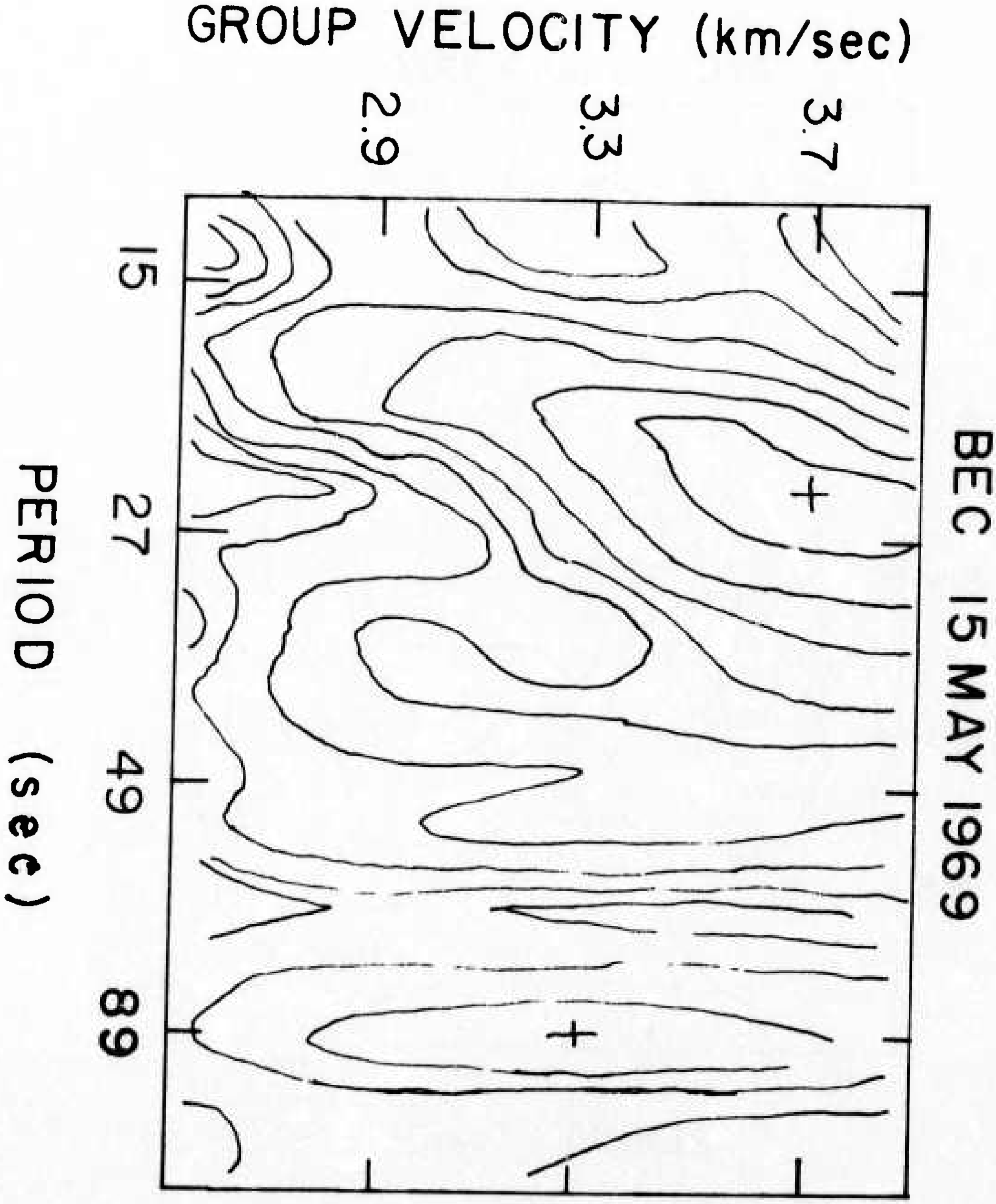

GROUP VELOCITY (km/sec)
36
4.0
4.4
15
27
49
89
PERIOD (sec)
NAT 8 JULY 1970

Figure 2e.


GROUP VELOCITY (km/sec)
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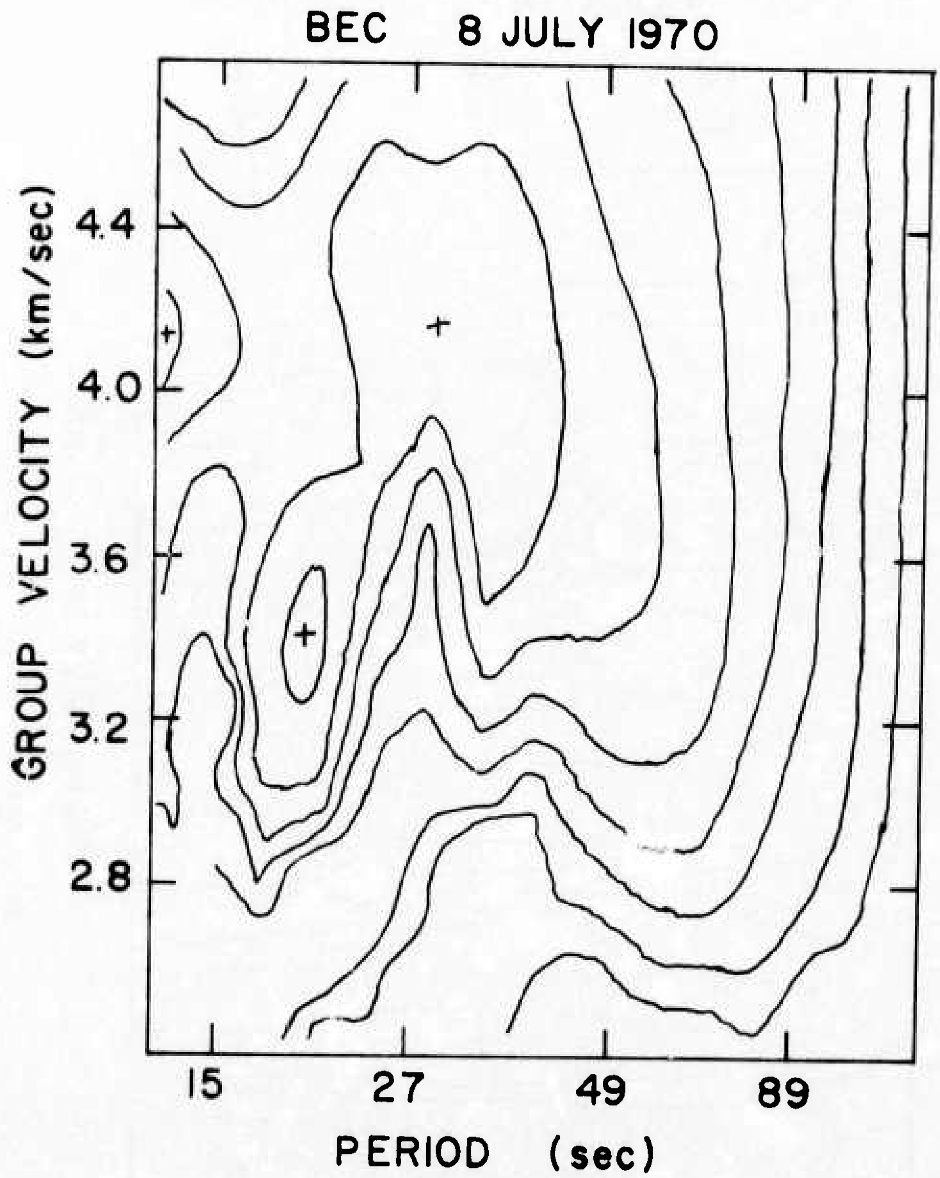
3.3
3.7
BEC 15 MAY 1969
PERIOD (sec)
15
27
49
89

Figure 2f.


BEC 8 JULY 1970
GROUP VELOCITY (km/sec)
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4.0
3.6
3.2
2.8
15
27
49
89
PERIOD (sec)

Figure 2g.

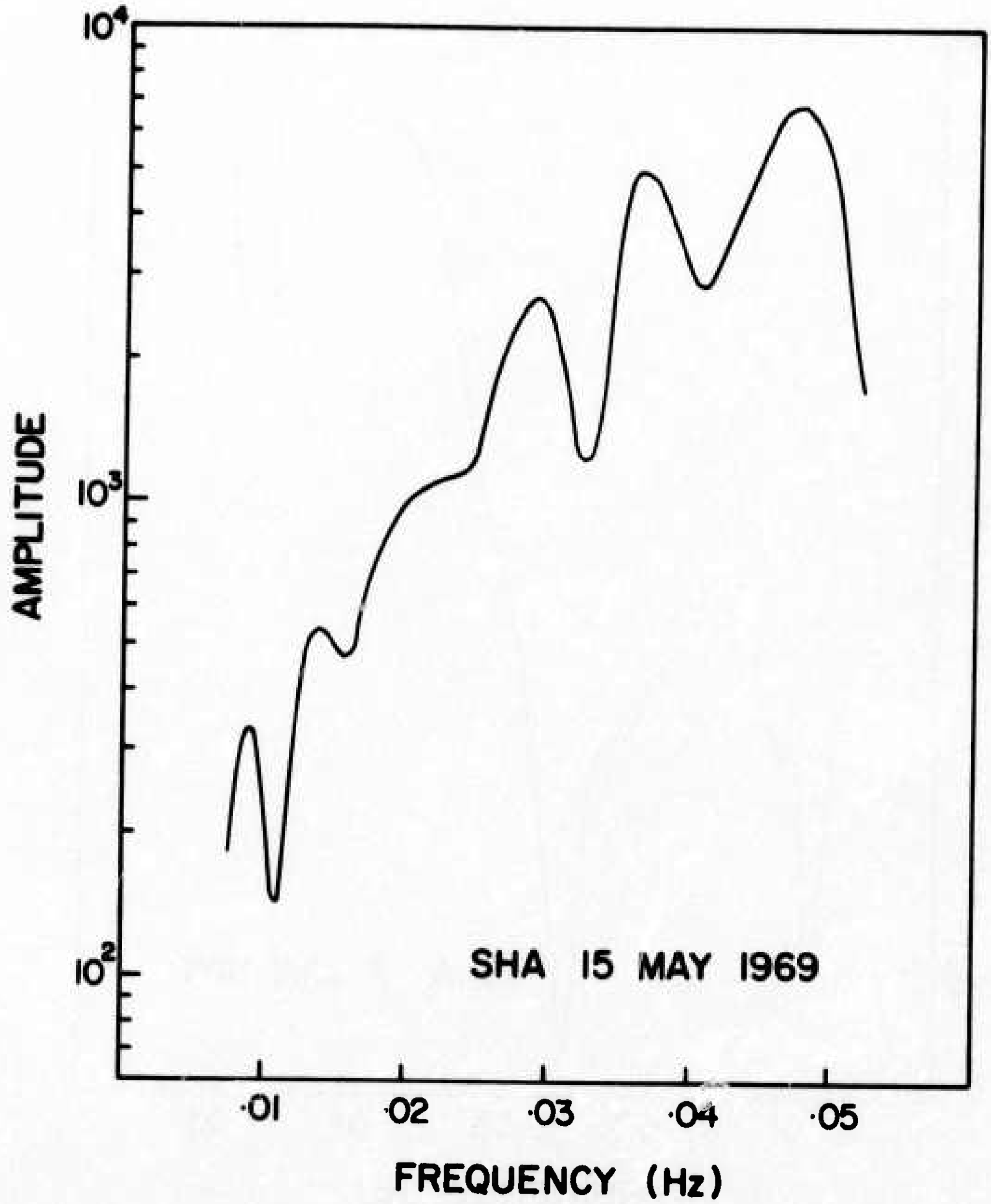

AMPLITUDE
10^4
10^3
10^2
SHA 15 MAY 1969
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 3a.

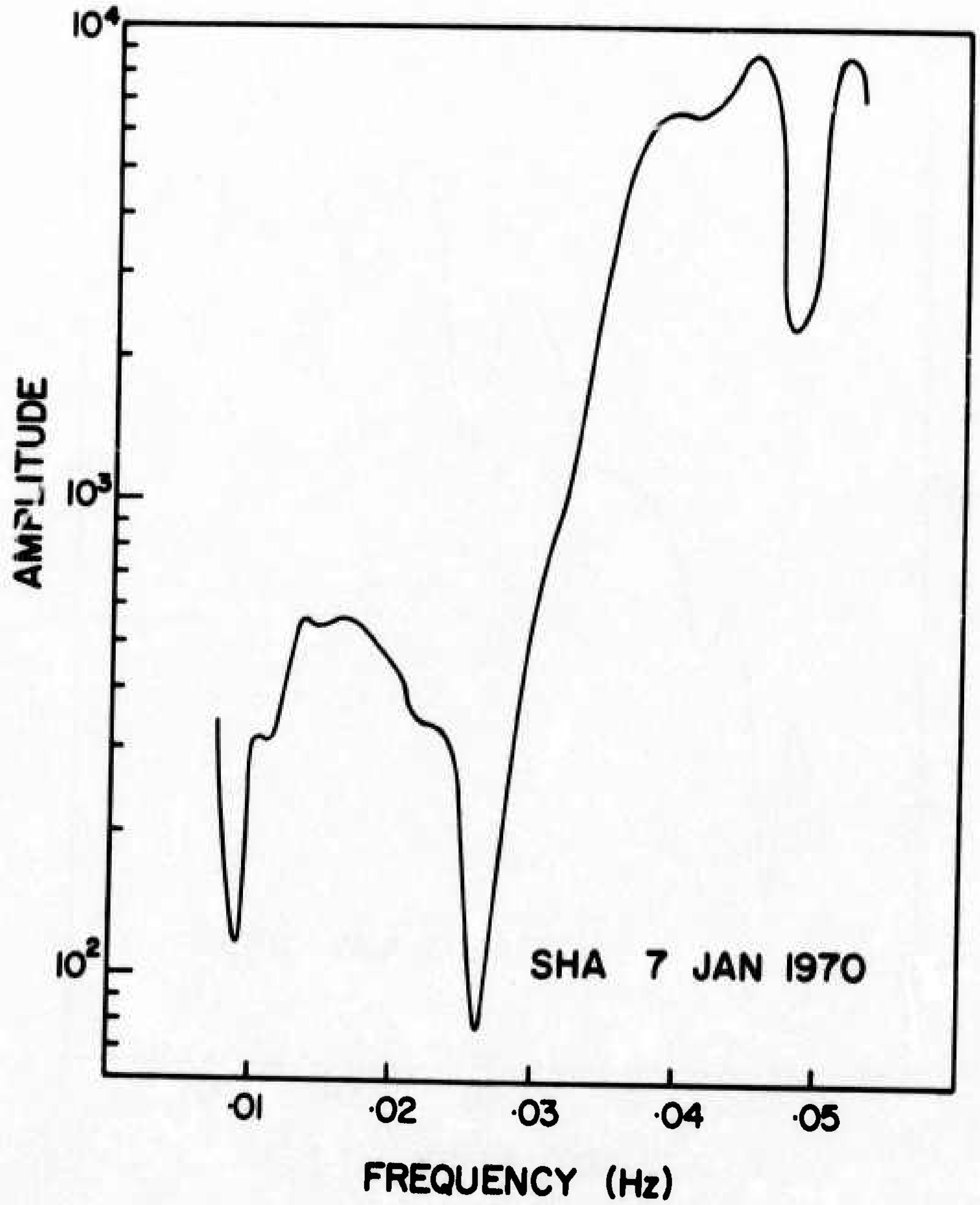
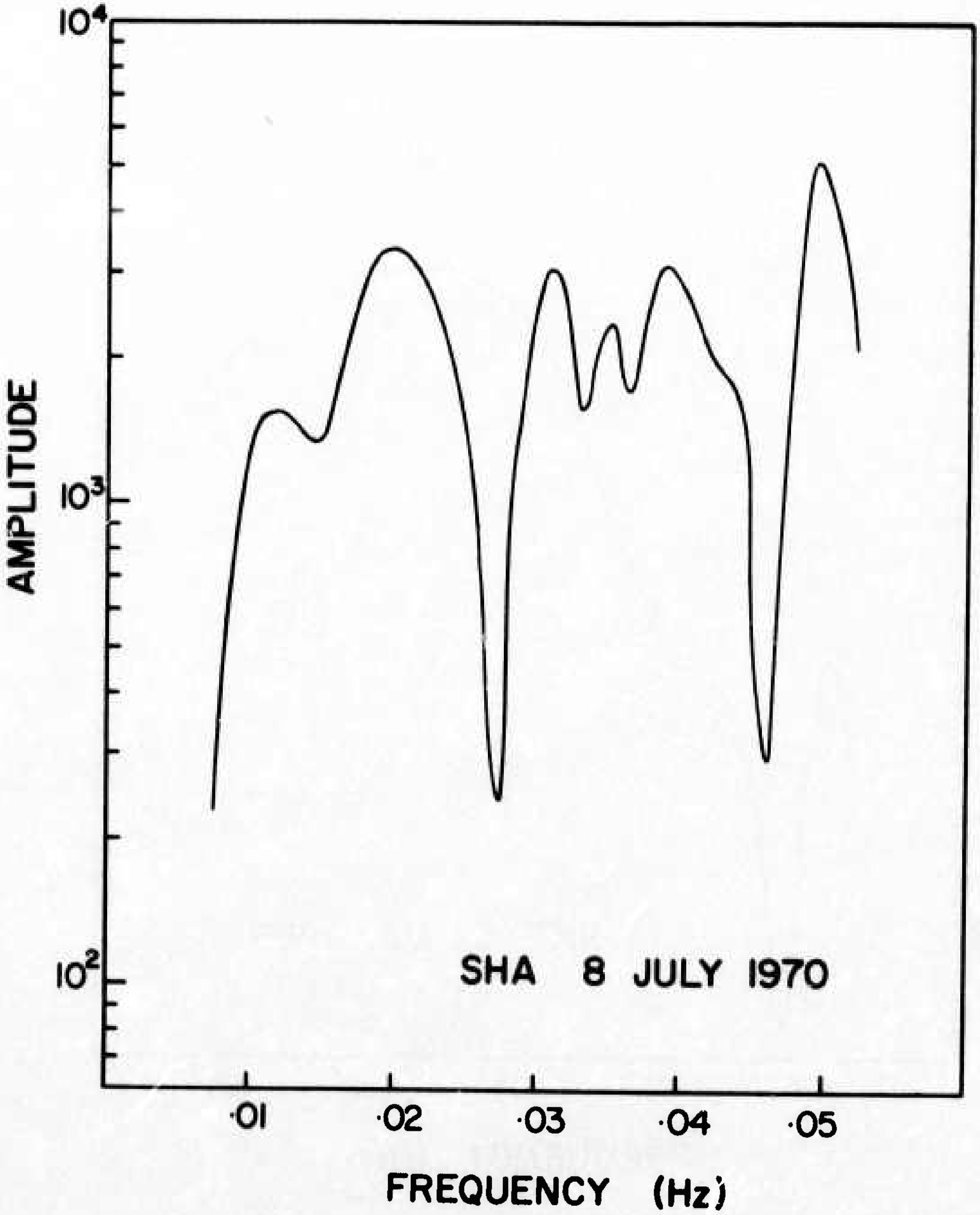

10^4
10^3
10^2
AMPLITUDE
SHA 7 JAN 1970
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 3b.



10⁴
10³
10²
AMPLITUDE
SHA 8 JULY 1970
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 3c.

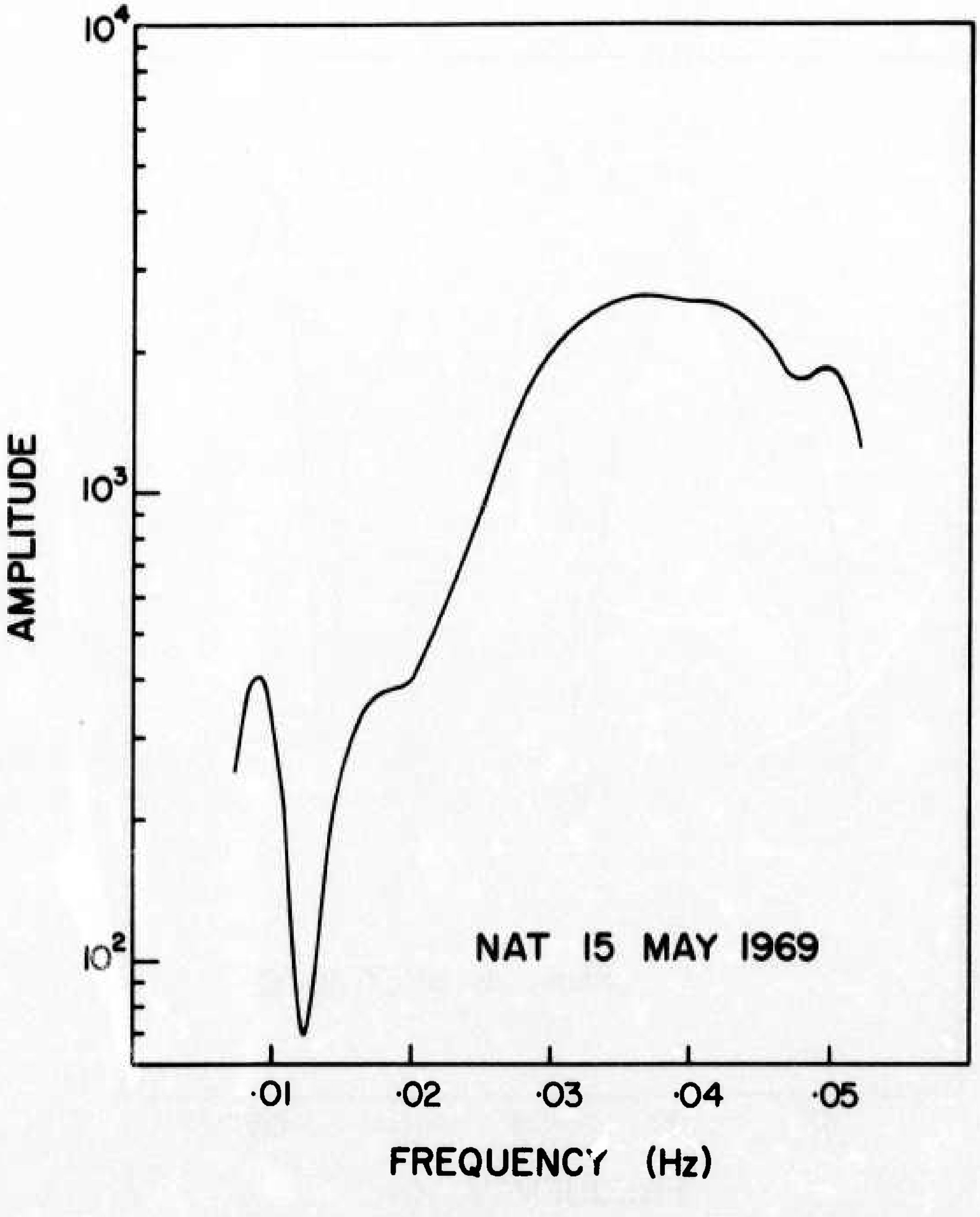
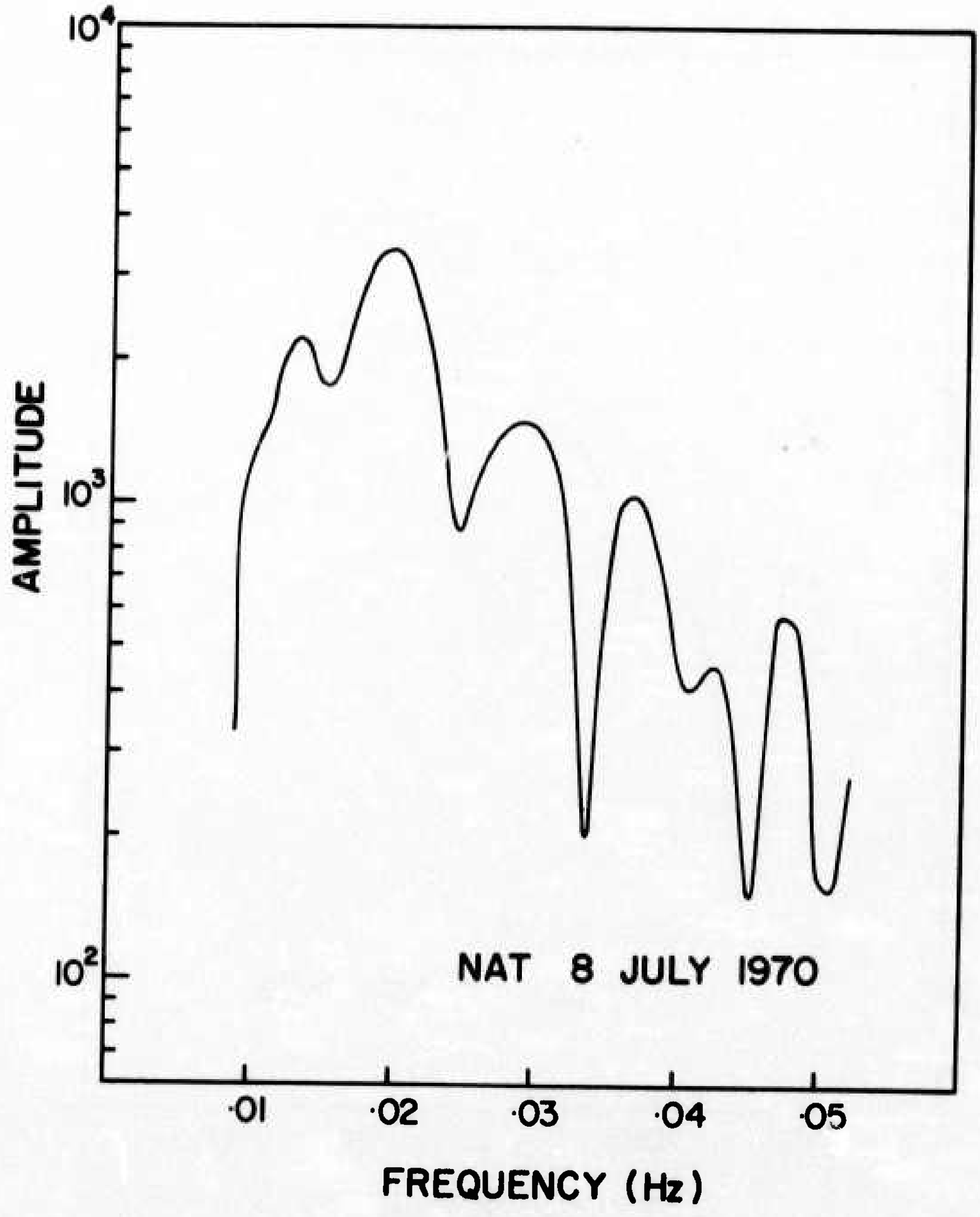
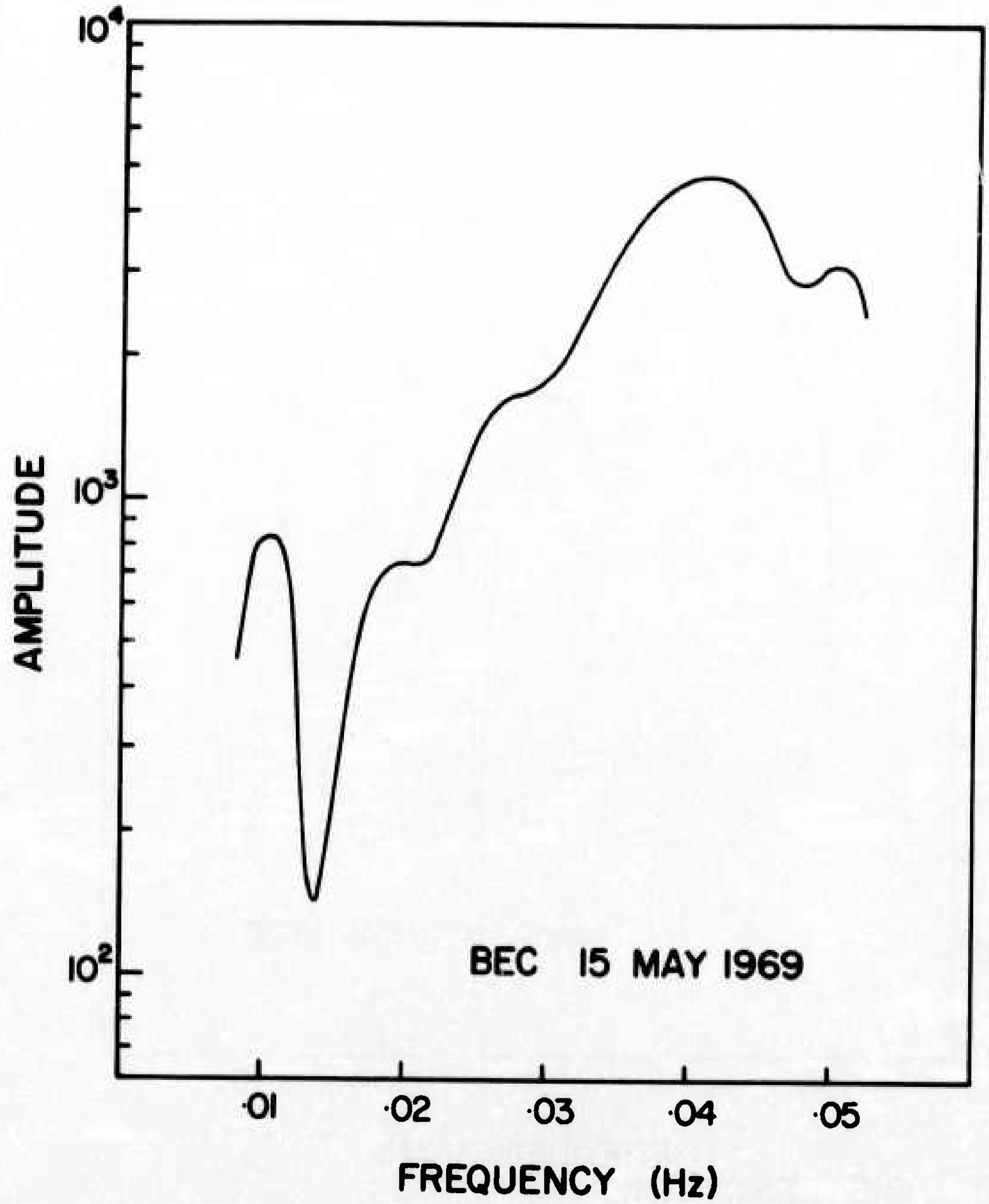

10⁴
10³
10²
AMPLITUDE
NAT 15 MAY 1969
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 3d.



10^4
10^3
10^2
AMPLITUDE
NAT 8 JULY 1970
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 3e.



10^4
10^3
10^2
AMPLITUDE
BEC 15 MAY 1969
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 3f.

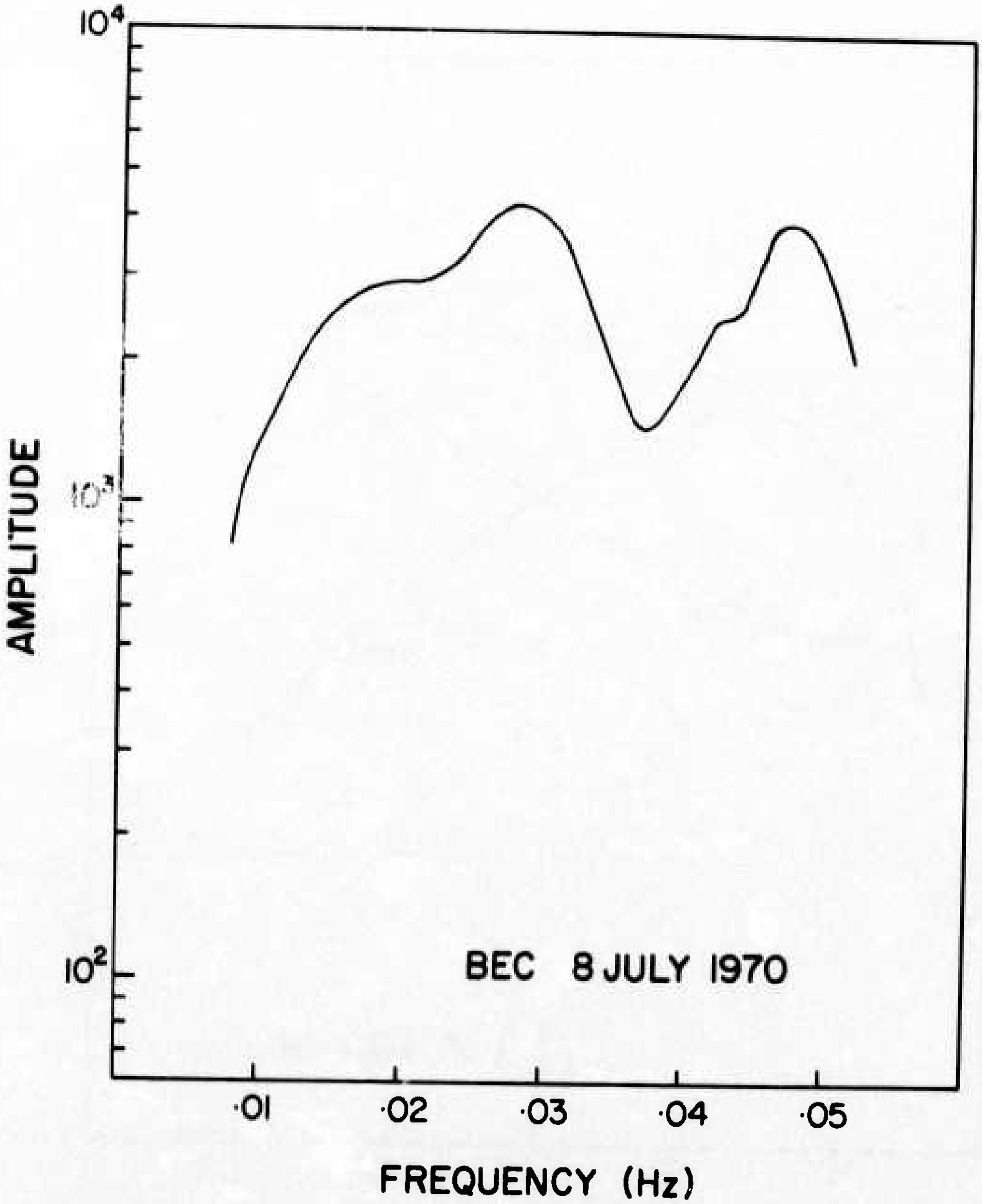

10^4
10^3
10^2
AMPLITUDE
BEC 8 JULY 1970
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 3g.

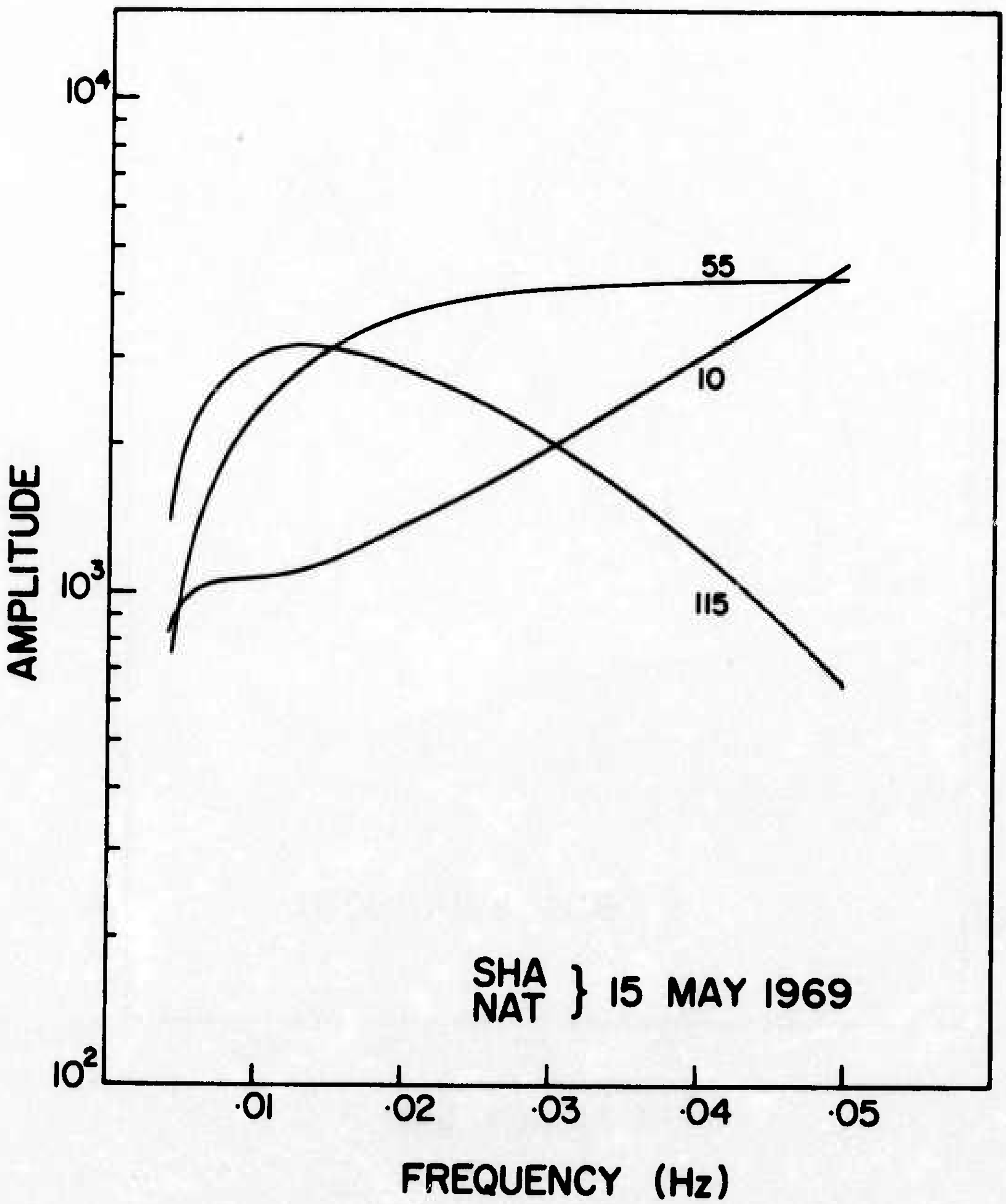

10^4
10^3
10^2
AMPLITUDE
55
10
115
SHA
NAT
} 15 MAY 1969
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 4a.

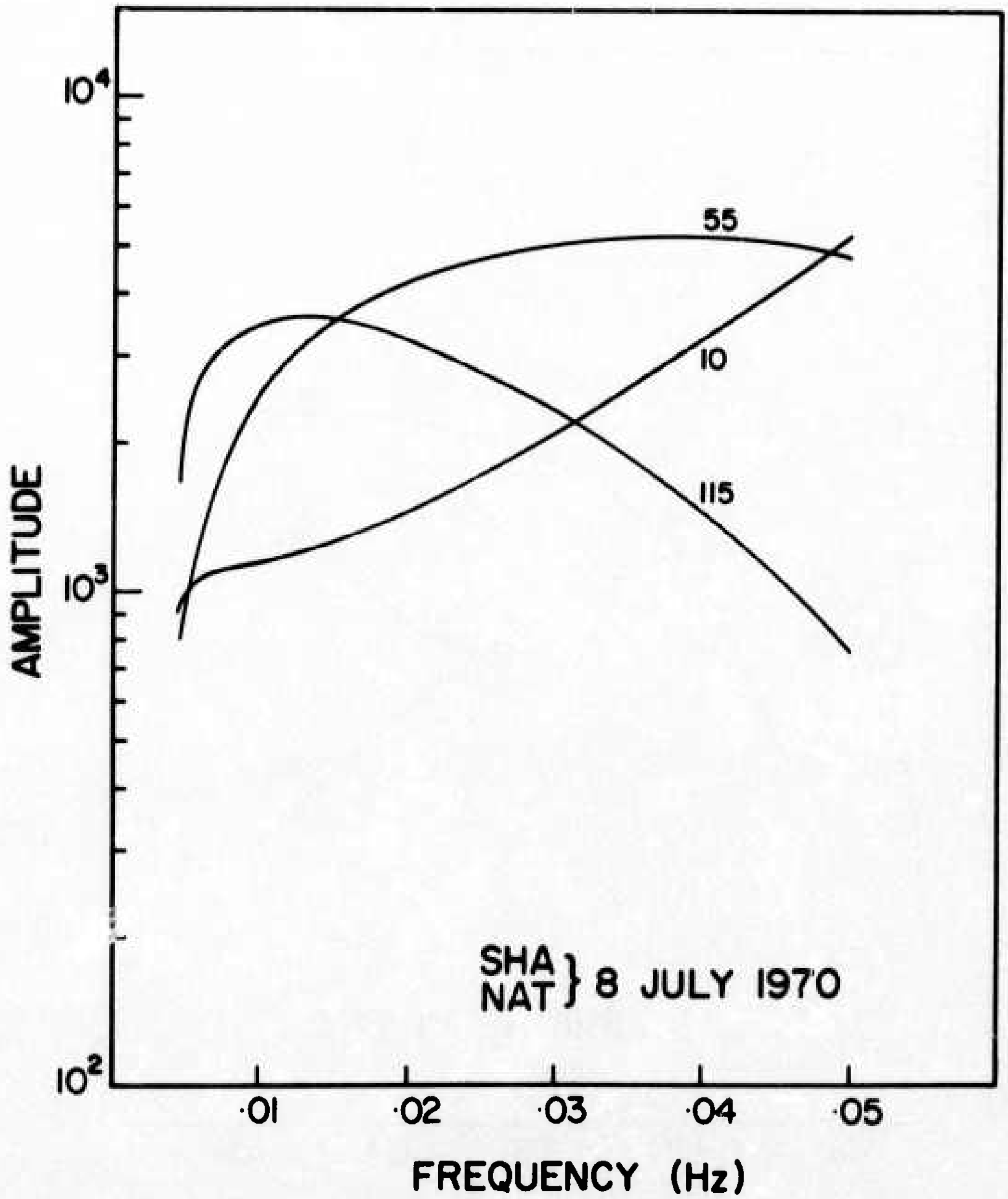
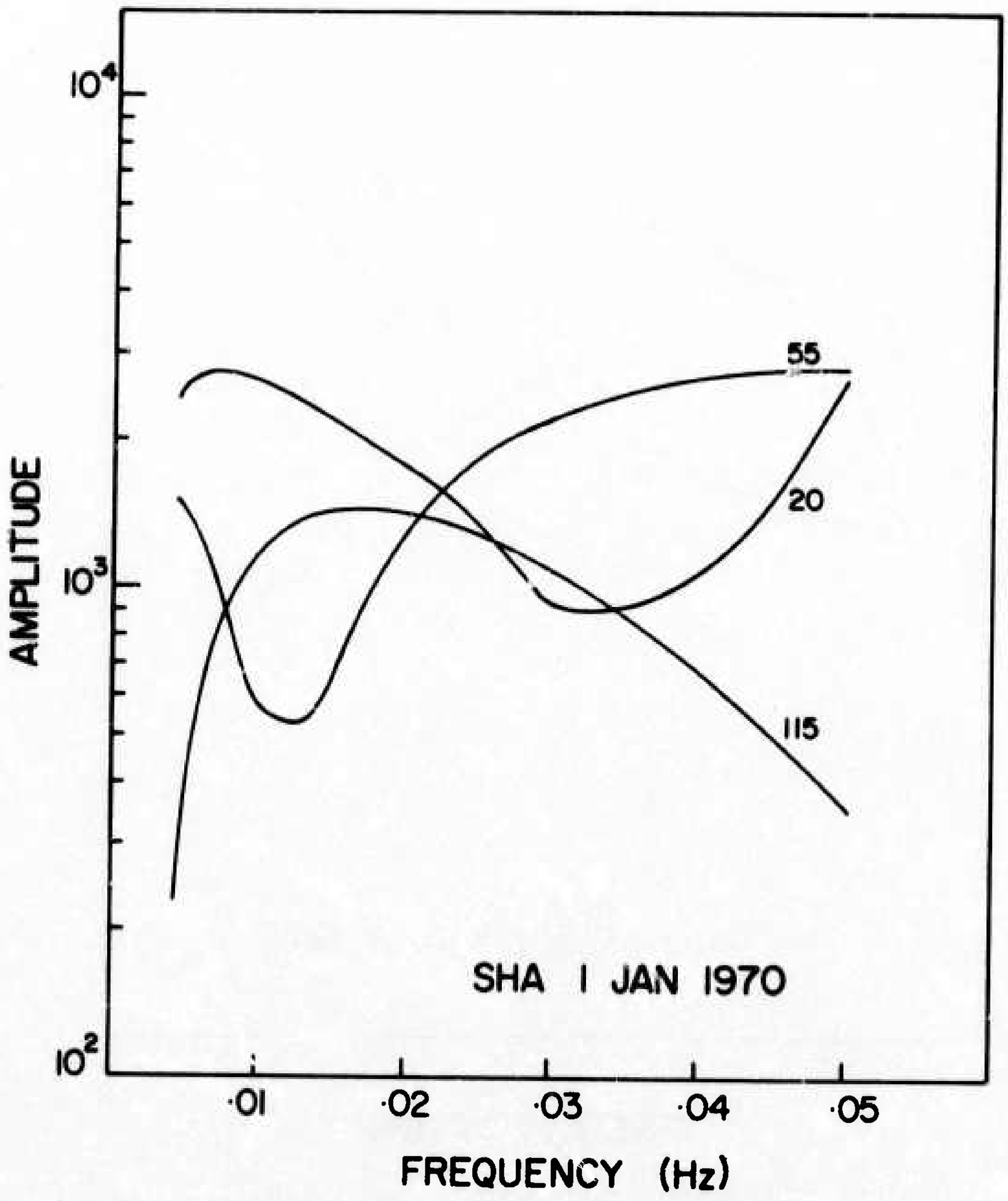
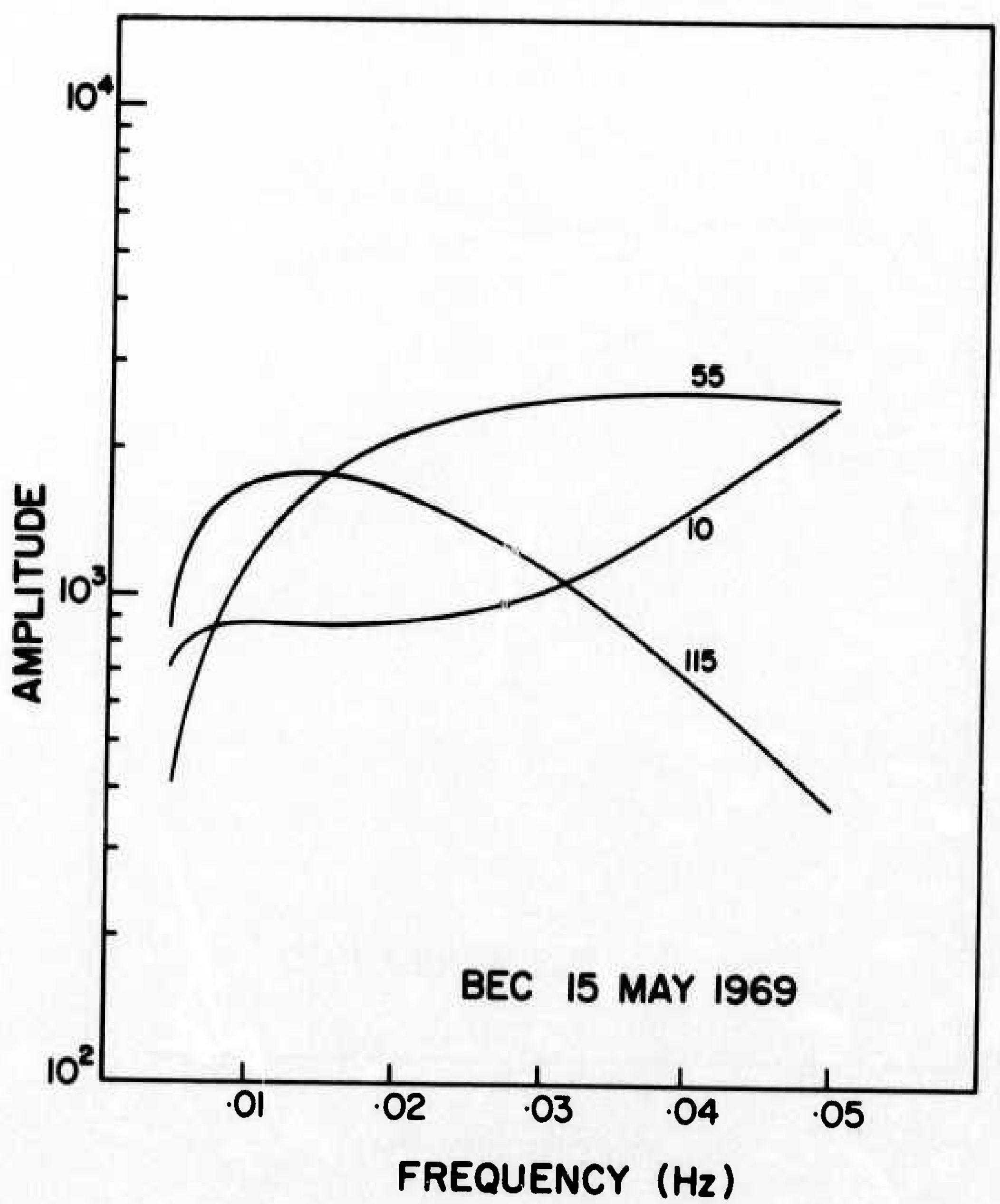

AMPLITUDE
10^4
10^3
10^2
55
10
115
SHA
NAT
} 8 JULY 1970
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 4b.



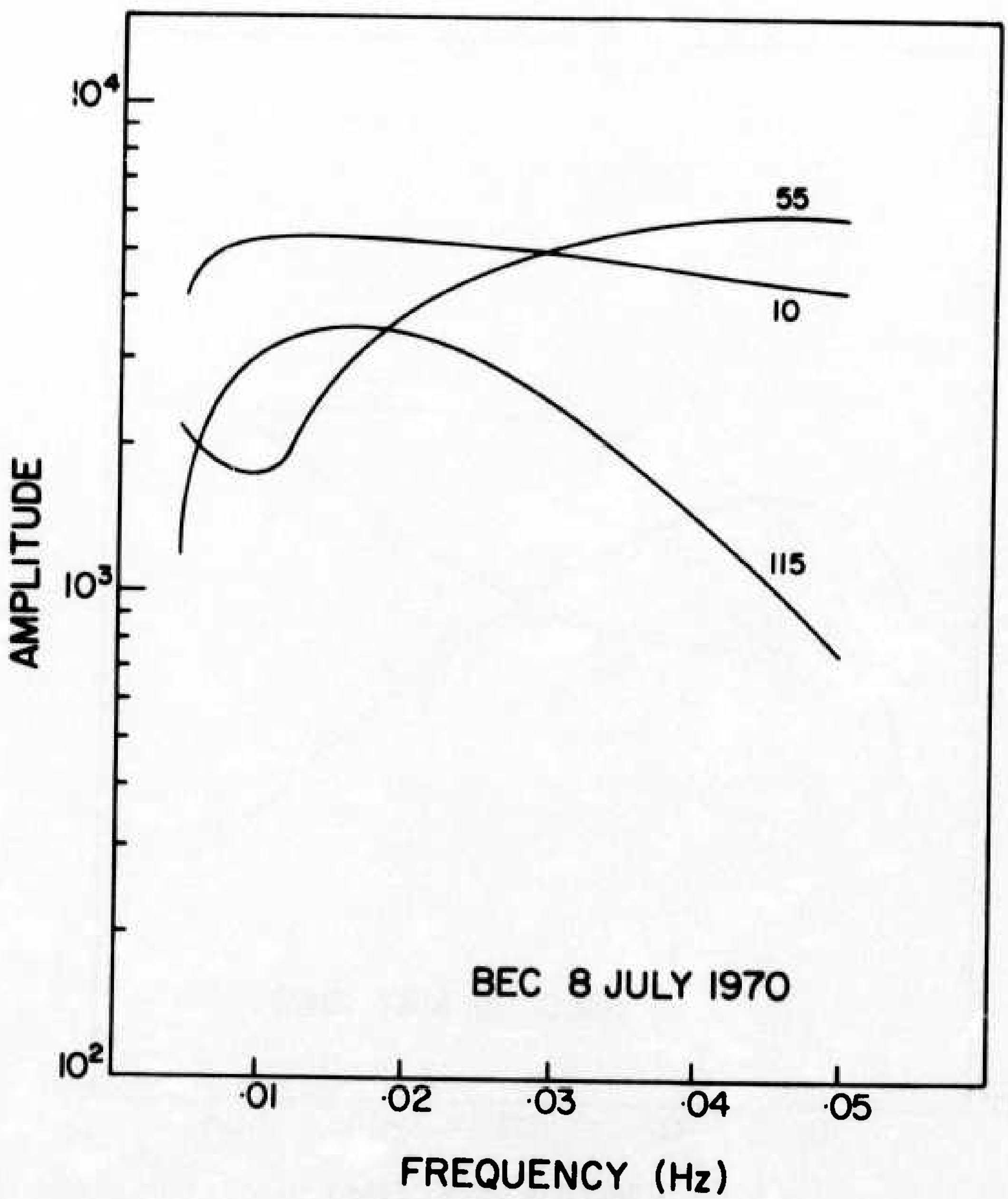
AMPLITUDE
10^4
10^3
10^2
55
20
115
SHA 1 JAN 1970
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 4c.



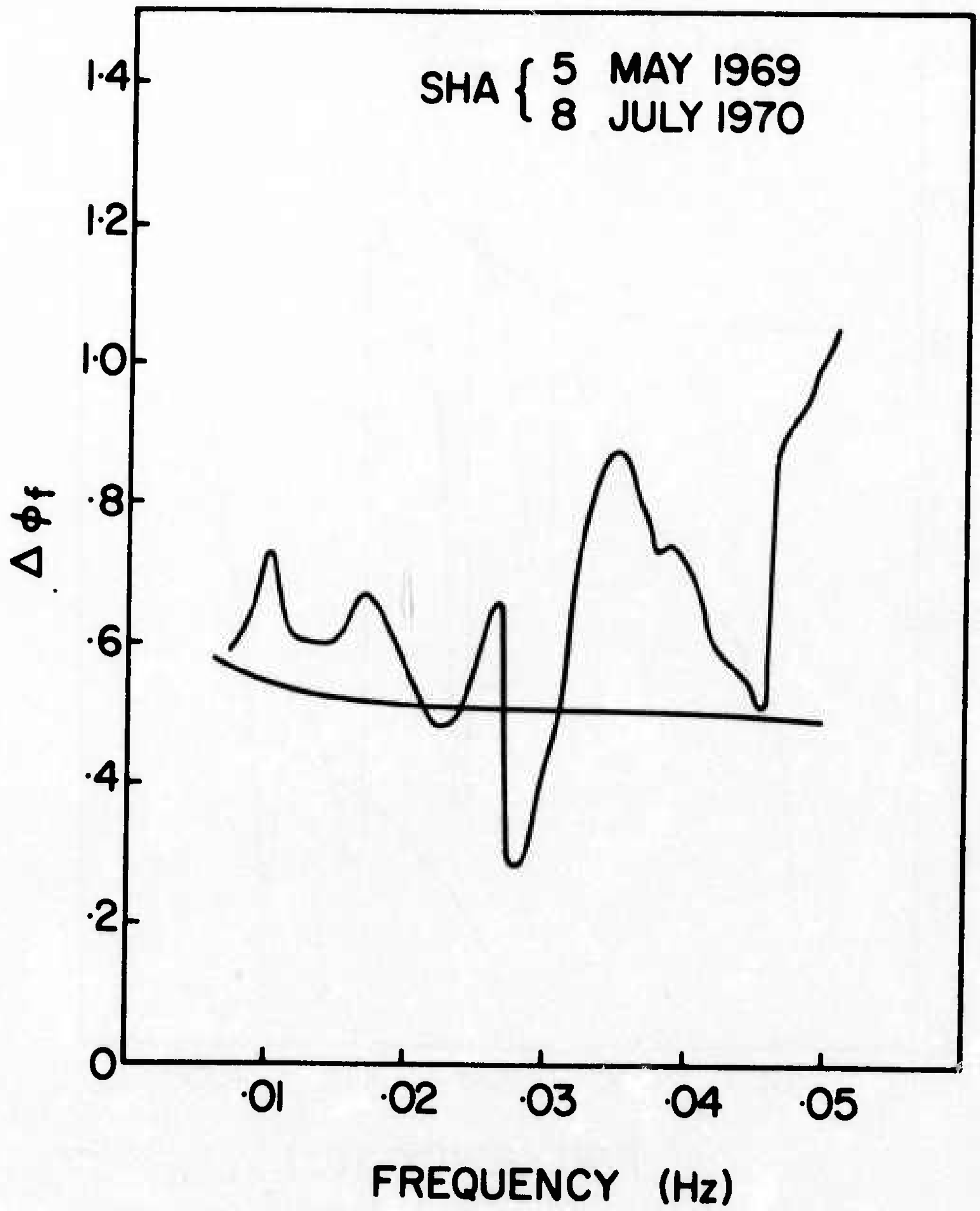
10⁴
10³
10²
AMPLITUDE
55
10
115
BEC 15 MAY 1969
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 4d.



10^4
10^3
10^2
AMPLITUDE
55
10
115
BEC 8 JULY 1970
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 4e.



SHA { 5 MAY 1969
8 JULY 1970
1·4
1·2
1·0
·8
·6
·4
·2
0
Δφf
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 5a.

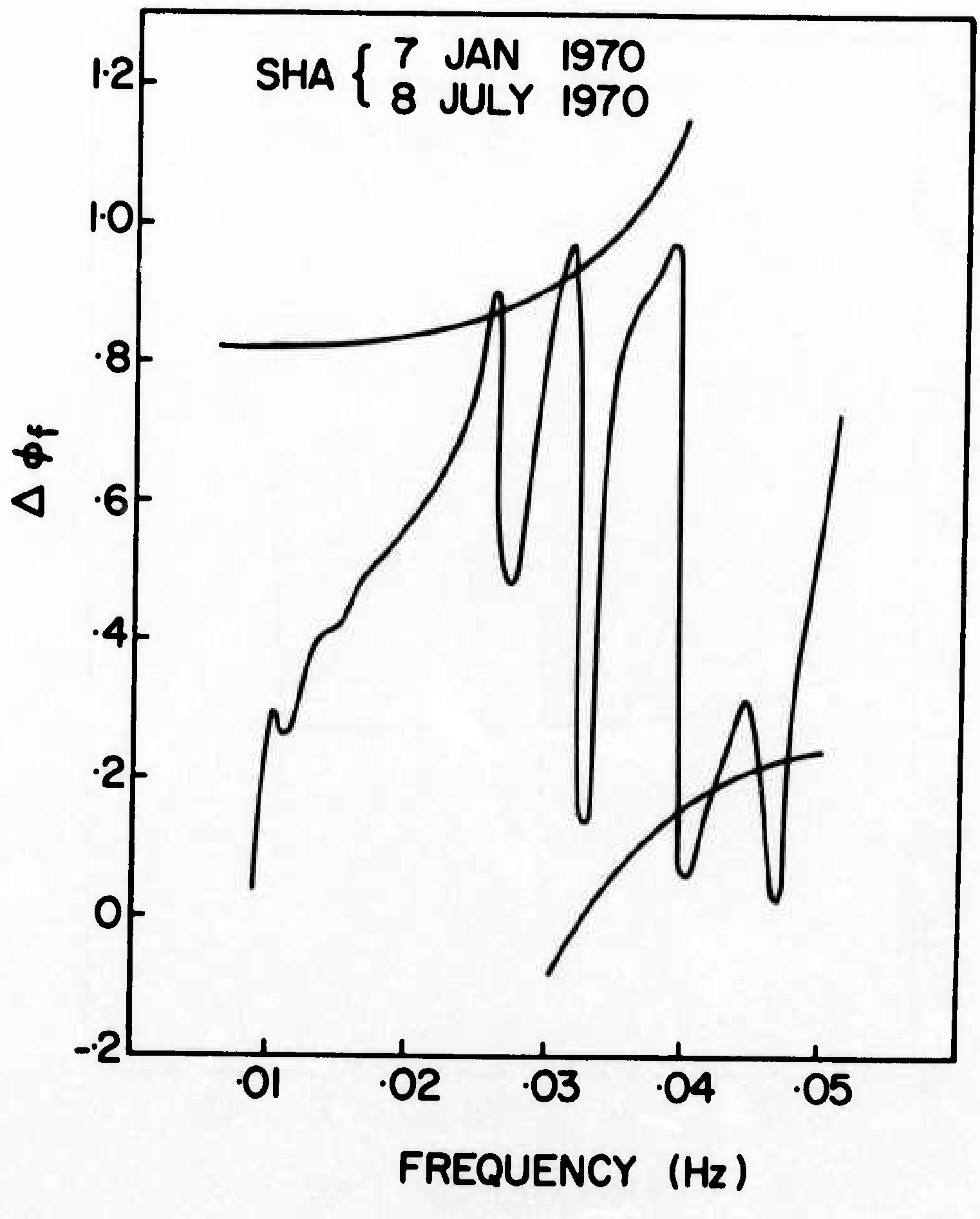

SHA { 7 JAN 1970
8 JULY 1970
1·2
1·0
·8
·6
·4
·2
0
-·2
Δ φf
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 5b.

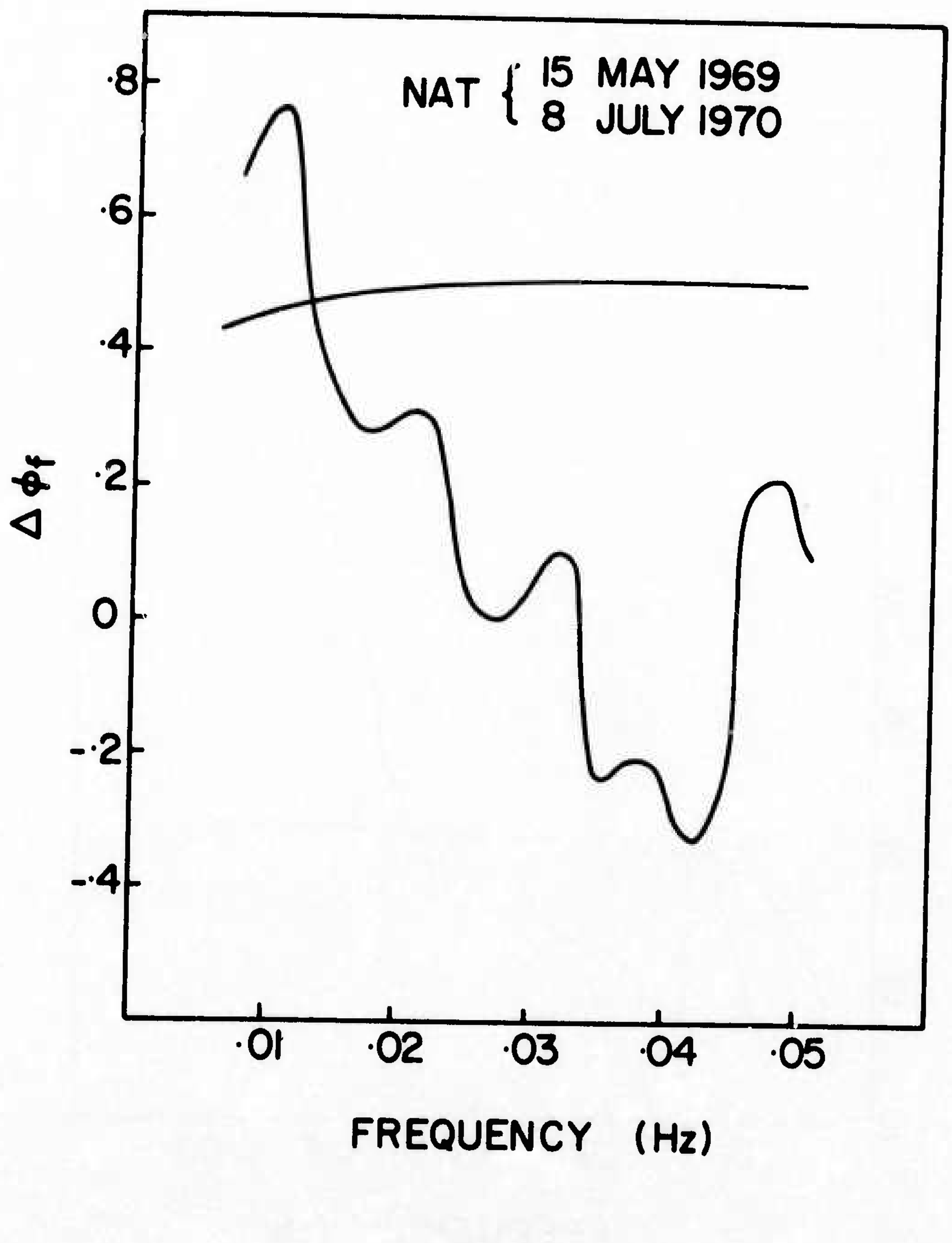
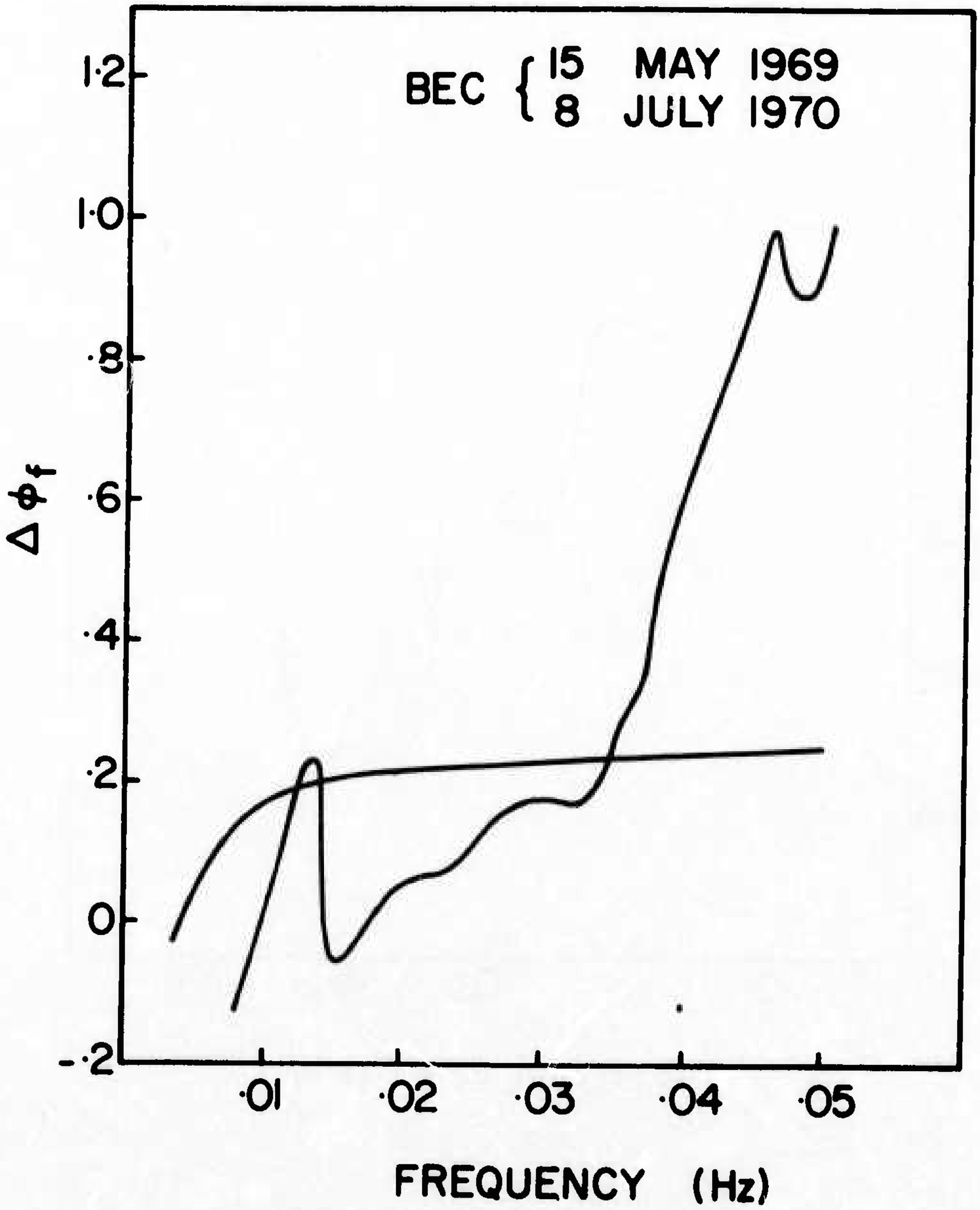

NAT { 15 MAY 1969
8 JULY 1970
·8
·6
·4
·2
0
-·2
-·4
Δφf
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 5c.



BEC { 15 MAY 1969
8 JULY 1970
1·2
1·0
·8
·6
·4
·2
0
-·2
ΔΦf
·01
·02
·03
·04
·05
FREQUENCY (Hz)

Figure 5d.